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JUNE 1938

ORDINARY MEETING.

(JOINT MEETING WITH THE INSTITUTION OF ELECTRICAL ENGINEERS.)

22 March, 1938.

SYDNEY BRYAN DONKIN, President, in the Chair,

supported by

Sir GEORGE LEE, O.B.E., M.C., President I.E.E.

The President extended a welcome to the President of the Institution of Electrical Engineers and to those Vice-Presidents, Past-Presidents and Members of that Institution who were present.

The Council reported that they had recently transferred to the class of

Members.

Ralph William Butler.
John Campbell Coutts, B.Sc. (*Glas.*).
Richard Howell Davies, D.S.O.
John Weller Sandford Fawcett.
Cecil Gorman.
Isaac Vincent Robinson.
Joseph Eric Swindlehurst, Jun., M.A. (*Cantab.*).

And had admitted as

Students.

William Brodie Acheson.
Robert Alexander Angus.
Edward Applewhite, B.A. (*Cantab.*).
Frederick Leonard Boulter.
Edward Frank Bowen.
Andrew Alexander Scott Brodie, B.Sc. (*Edin.*).
Ronald John Brown.
Angus Murray Buchan.
John McRoberts Buchanan.

Gordon Cameron.
George Frederick Chambers.
Ernest George Clark.
Philip Bolton Douglas Cooper, B.A. (*Cantab.*).
Samuel Beattie Craig, B.Sc. (*Belfast*).
Douglas Hugh Morley Edmunds.
Edward Mervyn Evans.
Clarence George Horatio Filor, B.Sc. (*Bristol*).
Edward Court Fisher.
Frank Alfred Halsey.
Michael Hardy.
James Mills Henry.
Francis Edward Henson.
Thomas Cornwell Michael Hodges.
Robert Moffat Hood.
Donald Crane Howard.
William Eric Killon Humphreys.
Harold Kenneth Johnson, B.Sc. Tech. (*Manchester*).
John Jones.
Thilliampalam Visvalingam Kanagasabai.
Evan Melfyn Lewis.
Kenneth Macpherson.
John Victor Coulson Mason.
Herman Merkel.
Gangadhar Bhaskar Modak.
Marshall Nixon, B.Sc. (*Durham*).
Benedict John Redmond O'Mahony, B.Sc. (*S. Africa*).
John Croft Parker.
Jack Edleston Pavitt.
Narahari Nilkanth Purandare, B.E. (*Bombay*).
Philip Marland Rambaut, B.A. (*Cantab.*).
Harold Henry Satterly, B.Sc. (Eng.) (*Lond.*).
Kenneth Henry William Sayer.
Kantilal Saburlal Shah, B.Sc. (*Bombay*).
Fred Sleath.
James Gordon Anstruther Smith.
Ralph Thomas Stokes, B.Sc. (*Birmingham*).
Devinder Kumar Subarwal.
Alexander Wylie Thomson.
Anthony Richard Titford.
Eric George Tyldesley.
Cyril Arthur Tysall.
John Philip Wain.
Douglas Sanders Warren.
William Robert Wells.
Mallroy Evan Wijesinghe.
Richard d'Avray Williams.
William Wright.
Edwin Thomas Edward Yates.

The following Papers were submitted for discussion, and, on the motion of the President, the thanks of The Institution were accorded to the Authors.

Paper No. 5172.

"Constructional Work of the Fulham Power-Station." †

By John Findlay Hay, M. Inst. C.E.

TABLE OF CONTENTS.

Introduction.

The works described in the Paper are those constructed on the first portion of the Fulham Borough Council's new generating station, and include :—

(1) The preliminary excavation of the main site to water-level and the enclosing of the area with steel sheet-piling ;
(2) The construction of the retaining walls and raft ;
(3) The intake- and discharge-tunnels, with their accompanying chambers, of the circulating-water system ; and
(4) The construction of a coaling jetty with the required dredging.

Preliminary Excavation to Water-Level.

The station lies east to west, with the boiler-house on the east, and is situated 60 feet from the river frontage, and 1,800 feet north along the west bank of the river Thames from the Wandsworth bridge. The total floor-area of the main building, consisting of the boiler-house, chimney-bay, turbine-house and circulating-water bay, is 9,500 square yards, with a provision for a further extension of the boiler-house by 4,000 square yards.

An examination of the site by survey and borings showed that the ground-level of the site could be taken at 18 feet above Ordnance datum, with ballast-top and water-level at Ordnance datum, the ballast being covered from ground-level by a deposit of river mud, stiff and uniform

† Correspondence on this Paper can be accepted until the 1st September, 1938.—Sec. Inst. C.E.

in character. At − 12 O.D. London clay was met, and this level was repeated throughout the whole area with the exception of a few local pockets disclosed during the constructional work. A boring taken some years previously at the old station near this site showed the London clay to be 150 feet in depth before the Thanet sands and chalk were touched.

The preliminary excavation by dragline machines was started in November, 1932, and by the end of January, 1933, 60,000 cubic yards of the river deposit had been excavated to ballast-top and, with the exception of the site of the east retaining-wall nearest the river, the ground was battered off, the toe of the slope coinciding with the back-line of the future walls. A careful check was then kept on the water-level at the ballast-top with relation to the river-tide, and it was found that the site water-level varied only by a few inches, in spite of the easterly end of the excavation being only 60 feet away from the river-wall.

Steel Sheet-Piling.

The area was enclosed by 15-inch by 5-inch "Universal Joist" steel sheet-piling and amounted to 13,500 square yards, including the provision for the boiler-house extension. The lengths of the piles ranged from 25 feet to 30 feet, giving a total weight driven of approximately 1,300 tons.

Driving commenced at the end of February, 1933, and was completed in 2½ months without any difficulty being experienced. The clay-level proved uniform, allowing the pile-length in all cases to be driven 5 feet beyond the required clay formation-level of the retaining-walls. Piling commenced on the line of the east wall, with the piling frames working westward along the north and south lines. Before these lengths were completed, the site had been dewatered by pumping at various temporary sumps constructed in the 12-foot depth of ballast.

Retaining Walls and Raft.

The walls were built in trench and are founded in the London clay. The construction of the south, east and west walls is of reinforced concrete ; the north wall, being of a temporary nature only to allow for the extension of the boiler-house, is in blue brindle brickwork.

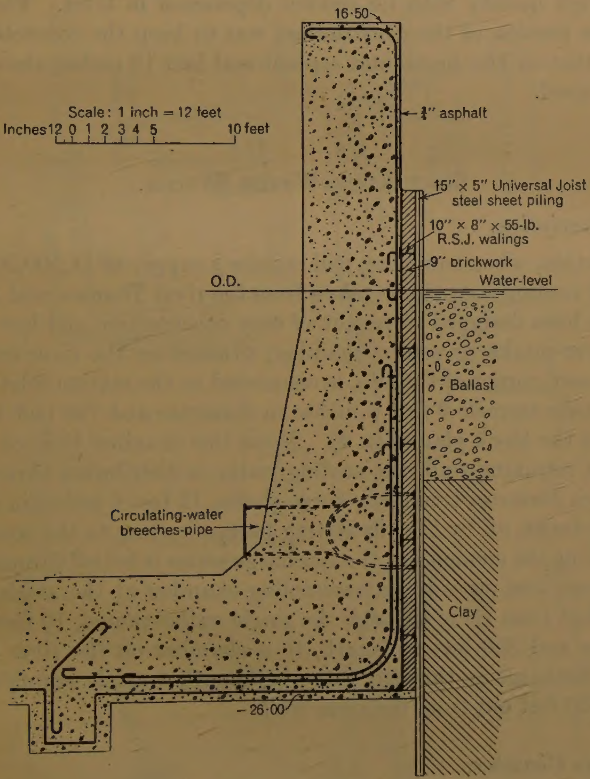
The mix in the concrete walls is of two grades, that around the reinforcing steel being a mix of 2 cwt. of cement, 4½ cubic feet of sand and 9 cubic feet of aggregate, whilst for the remaining portion of the section a mass mix of 1 part of cement to 4 parts of ballast was used.

The whole of the structure to wall-top is tanked by a ¾-inch layer of asphalt, the vertical seal at the back of the retaining-walls being spread on a 9-inch-thick screen of wire-cut brickwork.

Details of Construction.

During the progress of excavation, steel walings of 10-inch by 8-inch by 55-lb. section were employed on the back line of the trench and spot-welded to the pile-clutches. On bottoming up the trench, the horizontal seal was laid on a 12-inch thickness of concrete, and the brick screen was built between the steel walings and carried up to the required level. The

Fig. 1.



TYPICAL SECTION OF RETAINING-WALL.

asphalt seal was then spread in two layers of $\frac{3}{8}$-inch thickness over the whole lift of brickwork including the flanges of the rolled-steel-joist walings (*Fig. 1*).

In order to guard against any springing in the waling, which might have fractured the seal when the timber struts were struck, a portion of the concrete wall, but not to full sections, was built up between the struts to a level above the waling. It was then possible to remove the struts with safety and to complete the asphalt at their seating. This practice

proved satisfactory, and after its adoption no evidence appeared of any movement in the walings.

The raft is built in mass concrete with a mix of 6 parts of ballast to 1 part of cement, and has a general thickness of 12 feet. It was constructed in two operations, firstly up to the underside of the main grillages, and then by a mass filling to basement-floor level.

No difficulty was experienced during the construction of the raft, and the London clay beneath the 12-foot depth of ballast dumpling proved to be of high quality with no sudden depression in level. The hardest task in this portion of the construction was to keep the concrete work in step with that of the horizontal asphalt-seal laid 12 inches above ground formation-level.

Circulating-Water System.

General Description.

The station, when complete, will require a supply of 14,500,000 gallons per hour of cooling water to be taken from the river Thames, and the whole system has been designed to permit of easy construction and low cost.

The river-intake or screen chamber, situated on the river-frontage at the south-east corner of the site, is connected to the station inlet-chamber by twin intake-tunnels 9 feet 6 inches in diameter and 720 feet in length, as shown in the block plan (*Fig. 2*). From this chamber built at the back of the west retaining-wall, the cooling water is distributed through short 6-foot 6-inch diameter tunnels to surge-shafts, 12 feet 6 inches in diameter, where it is drawn off by the circulating pumps leading to the condensers.

On leaving the condensers, the discharge water is led off through 5-foot-diameter cast-iron pipes to an assembling chamber at the station outlet-chamber, and from there through the single outlet-tunnel, 10 feet 6 inches in diameter and 350 feet in length, to a chamber on the river frontage. The final discharge is through three bellmouth tunnels emptying on to an apron 120 feet out from the river-wall.

River-Intake Chamber.

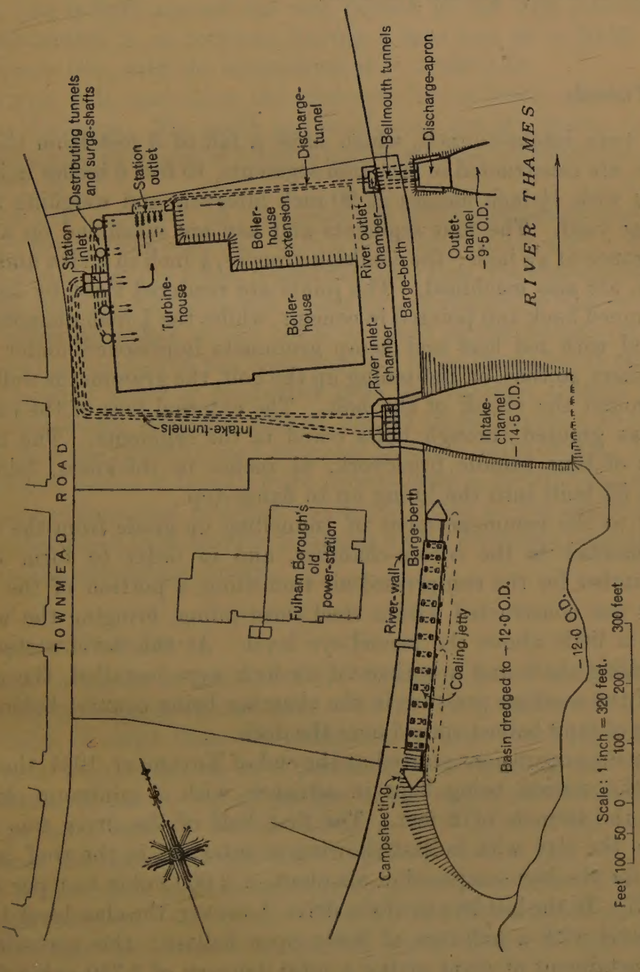
This chamber, containing the coarse and fine screens, penstocks and intake-tunnel eyes, was constructed in a cofferdam, 4,000 square feet in area, with two narrow extensions to allow for the construction of training walls to support the inflow-channel section after the completion of dredging.

The chamber is constructed in concrete and is founded on blue clay (— 25·0 O.D.) with the sheet-piling 5 feet below this level. The west wall containing the eyes (invert-level — 17·50 O.D.) and the north and south walls are 9 feet in thickness and unreinforced. The east wall, which is the re-built portion of the river wall, has a thickness of 2 feet and is reinforced

by rolled-steel joists, and in its lower portion the panels of the coarse screen are built from intake-apron level (— 14·50 O.D.) to screen-top (— 3·0 O.D.); on the river face there is a protecting floating boom set in guides.

At a distance of 8 feet inwards and in parallel is built the 3-foot-thick

Fig. 2.



General Plan of Station, showing Coaling Jetty and Circulating-Water System.

penstock wall allowing for six penstocks, each 9 feet 6 inches by 3 feet 6 inches, whilst at a further distance of 15 feet is built the fine-screen wall with apertures leading to the tunnel-eyes.

The chamber is divided by a party-wall built at right angles to the river-frontage, thus allowing either tunnel to be operated separately, whilst for constructional purposes each half of the chamber is divided into three

(invert-level — 19·50 O.D.), with a screen unit housed in each of the six cells. The screens are of Messrs. Brackett's vertical revolving-band type, with the revolving axis set in parallel with the flow so that on both sides of the screen case the ascending and descending screen band is capable of filtration. Each screen is operated by a separate motor and is capable of delivering 2,400,000 gallons per hour.

Intake-Tunnels.

The twin intake-tunnels, which have a fall of 3 feet from the river-chamber, are constructed of cast-iron segments, 10 feet 6 inches in internal diameter with $4\frac{1}{2}$-inch flanges at 20-inch intervals and weighing $2\frac{1}{2}$ tons per linear yard. The four segments and key are machined on all faces to a tolerance of $\frac{1}{50}$ inch; the caulking grooves, $\frac{1}{4}$ inch in width and $\frac{3}{4}$ inch in depth, are also machined. The joints are rendered tight by lead wire well stemmed back and pointed in cement, whilst the $\frac{7}{8}$-inch diameter bolts are sealed with red lead and hemp grummets imprisoned under dished steel washers, so that, on tightening up the bolt, the grummet is well forced home around the shank of the bolt. The external face of the cast-iron lining was grouted through holes cored in the segments. The internal lining is of blue brindle brickwork, $4\frac{1}{2}$ inches in thickness, laid on a concrete fill built into the lining up to flange-top.

Prior to the commencement of tunnelling up grade from the station intake-chamber to the screen-chamber, and in order to form an air-tight chamber for the compressed-air tunnelling, a portion of the former chamber was constructed within steel sheet-piling, bringing the walls to a height a little above the tunnel-eye level. At this level a steel deck with winding shaft and a horizontal air-lock were installed, the upward thrust of the working pressure in the chamber being counter-balanced by a loading of sand ballast spread over the deck.

Tunnelling operations started at the end of November, 1934, the tunnel nearest the station being kept in advance, with a minimum clearance between the tunnels of 2 feet. The first half of the drive was almost wholly in the clay with ballast showing at intervals in the roof, and did not call for the low-compression air-plant of 2,000 cubic feet per minute to the full. In the last length of the drive, however, the clay-level dropped to axis-level with a half-face of fairly open ballast; this necessitated a further instalment of plant giving a total delivery of 2,750 cubic feet per minute. The working pressure ranged from 5 to 10 lb. per square inch.

On approaching the eyes at the screen-chamber, the clay rose in a most convenient manner enabling the steel piling to be cut away in free air and the tunnel-iron carried well into the concrete eye.

The tunnels were hand-driven, the employment of a shield being out of the question on account of the right-angle bends in the alignment.

On the completion of tunnelling at the end of March, 1935, the average rate of progress in each tunnel was found to be 50 feet per week.

Station Inlet-Chamber.

This distributing chamber lies on the east and west centre-line of the station, and is built against the rear portion of the west retaining-wall. The construction is in concrete, having a base area at — 30·00 O.D. of 1,600 square feet, with the invert-level at — 27·00 O.D.

The west wall, containing the inlet eyes (invert-level — 20·50 O.D.), is 6 feet in thickness. The north and south walls are of a similar thickness, each containing two eyes of 6 feet 6 inches internal diameter (invert-level — 16·87 O.D.).

There is a party-wall on the centre line of the station and another wall 10 feet in front of the west wall, with a penstock fitted in each. There are also penstocks over the 6-foot 6-inch diameter eyes, the arrangement being that with only one intake-tunnel operating, cooling water may be supplied to any generating unit to the north or south of the station centre-line, thus allowing one-half of the intake-system to be examined at any time.

The cooling water is conducted from this chamber through the four short 6-foot 6-inch diameter tunnels, similar in construction to the main tunnels, into the 12-foot 6-inch diameter cast-iron surge-shafts ; these are lined with 4½ inches of brindle brick (invert-level — 24·00 O.D.), and have a specially constructed cast-iron connexion fitted to the single flange of the breeches-pipes built into the retaining wall. From this point the water passes to the circulating pumps.

Station Outlet-Chamber.

In this chamber is assembled the discharge-water delivered by the 60-inch diameter pipes (invert-level — 15·50 O.D.), connected to the condenser units, of which there will ultimately be five. Each pipe discharges into a twin well connected by a penstock, thus enabling any unit to be closed down, whilst the second portion of the well is able to diminish any undue pressure exerted on the ceiling (— 3·0 O.D.) of the assembling chamber at the rise of the tide (H.W.O.S.T. + 14·03 O.D.).

The construction is in concrete with a heavily-reinforced wall on the piped side (between — 25·0 and + 20·0 O.D.). The assembling chamber, with the single outlet-tunnel at its end, has a volume of approximately 9,800 cubic feet.

Outlet-Tunnel and River-Outlet Chamber.

The outlet-tunnel, 10 feet 6 inches in internal diameter and 350 feet in length with a 3-foot fall, is similar in construction to the intake-tunnels, but with the cast-iron segments of 11-foot 6-inch internal diameter, with

$4\frac{7}{8}$-inch flanges 20 inches apart. The segments weigh 2·8 tons per linear yard, and have a lining of Accrington brick.

In order to provide an air-tight chamber from which the tunnelling operations could be driven inland up the outlet-tunnel and towards the river into the three bellmouth tunnels, it was necessary first to construct the river-outlet chamber on the river-frontage at the north-east corner of the station site.

This chamber is built in concrete with walls 6 feet in thickness. The rear wall contains the 10-foot 6-inch diameter outlet-tunnel eye (invert-level — 21·00 O.D.); the new portion of the river-wall contains the three eyes, 8 feet in diameter (invert-level — 21·00 O.D.), leading through the bellmouth tunnels to the discharge-apron. The invert of the chamber is at — 26·0 O.D., with ground formation 4 feet below, and the chamber was built within a cofferdam.

As in the case of the station-inlet site, an air-tight deck was constructed just above the tunnel-eye level, but on this occasion it was bolted down to steel girders built into the walls. The winding shaft and horizontal air-lock at ground-level were similar in design to the intake-chamber.

In order to avoid a risk when tunnelling in both directions that a possible heavy inflow occurring in the bellmouth length might cause flooding of the main-outlet face and grave danger to the men, the engineers gave instructions that the driving of the main outlet should be first completed.

Tunnelling operations started at the beginning of March, 1935, and were completed in 8 weeks, giving an average rate of progress of 45 feet per week. Clay-level throughout the drive appeared a little above axis-level, with the remainder of the face in close ballast. The provision of 2,000 cubic feet per minute by the low-compression plant proved adequate, the working pressure required being from 5 to 8 lb. per square inch.

Bellmouth Tunnels and Discharge-Apron.

The three bellmouth tunnels, each 70 feet in length and terminating in concrete eyes at the apron, are constructed in cast-iron segments, increasing in diameter from 9 feet 6 inches to 12 feet (invert-level — 21·0 O.D.). Concrete head-walls make good the weakness at the change of section, whilst the internal lining is in concrete finished with a $\frac{3}{4}$-inch rendering of 2-to-1 cement applied by a cement gun.

The discharge-apron, constructed in a cofferdam, is of concrete, 50 feet by 60 feet, with an average thickness of 5 feet. There are training walls at the side of the apron, whose invert rises steeply from — 21·0 O.D. to river-bed level at — 6·50 O.D.

Penstocks, under separate control and operated at the river-outlet station, are fitted to each tunnel entrance at that point so that, when

required, any portion of the apron may receive special cleansing by increasing the discharge-velocity of the tunnel opposite that portion.

In preparation for tunnelling under the river-bed, a row of steel sheet-piling was driven on both sides of the tunnels, extending from the river wall to the cofferdam in which were constructed the discharge-eyes and apron. Between these lines of piles (with top-level + 5·0 O.D. and the toe at tunnel-axis, − 17·0 O.D.) a clay blanket, 5 feet thick, was deposited. The cofferdam, containing the discharge eyes and apron, was constructed with Krupp No. 3 section steel sheet-piling, the piles being 49 feet in length with a top-level of + 19·0 O.D., and the sides of the dam being 60 feet in length.

Every possible care was taken to ensure the stability of the dam during construction and during its use by adequate internal supports and ties, both across the top and from the dam to the shore. Even then there were moments of anxiety at high tide on the daily arrival of tugs with long tows of petrol barges to be berthed at a neighbouring wharf, whose water boundary was less than 10 feet away to the north; on such occasions the men working in the dam were brought to the surface until all craft were securely moored.

Tunnel-driving started beneath the blanket in May, 1935, and was completed in 6 weeks, only one face being open at a time in the order of centre tunnel, north tunnel and south tunnel. On reaching the dam a concrete collar was built into the bosom of the piles, the compressed air was taken out of the tunnels, and the cast-iron lining extended through into the eyes from within the dam.

The ground beneath the river-bed proved better than had been anticipated, ballast showing at about 2 feet below the crown of the tunnel. The working pressure used ranged from 6 to 12 lb. per square inch at high tide, and the supply of 2,300 cubic feet of air per minute was more than adequate. The whole operation was greatly facilitated by the provision of the piling enclosure and the clay blanket.

Coaling Jetty.

The jetty, 350 feet in length and 35 feet in width, and capable of berthing and off-loading two 2,300-ton colliers at a tide, is situated 200 yards upstream and south of the power-station (*Fig. 3*, facing p. 12), and provides a clearance of 25 feet from the river-wall for the berthing of barges.

Caisson Foundations.

The decision to use caissons as the most suitable form of foundation was arrived at after an examination of the conditions at the site. Opposite the jetty, and 60 feet away from the river-wall, the Fulham Council's existing generating station was operating under a heavy load.

The frontage-area for the whole length of the jetty, except those portions occupied by coaling hoppers, and silt and screening chambers forming part of the cooling-water system, was stacked with a heavy load of coal.

A careful examination of the river-wall, which was founded on a coarse ballast 2 feet above the clay, and constructed in concrete with a very slender section, showed that vertical fractures had appeared on the face. There was evidence that anchor ties had been provided, but their present value was difficult to determine.

From these observations it was felt that, with the heavy surcharge of coal which had to remain during the construction of the jetty, the prolonged stability of the wall would certainly be in doubt. Any form of open excavation for foundations on the shore causing a drag towards the river, or vibration from heavy piled foundations, would undoubtedly affect the stability of the wall, or even result in its complete collapse, and this would mean a severe interference with the work of the generating station. It was, therefore, decided to use caisson foundations.

The caissons, fourteen in number, are spaced at 28-foot centres, with the exception of the last two bays at each end which are at 21-foot centres. Each shell, 31 feet 6 inches by 9 feet by 20 feet, is constructed in $\frac{1}{2}$-inch mild-steel plates with 4-inch by $3\frac{1}{2}$-inch by $\frac{3}{8}$-inch angles, and 6-inch by 4-inch by $\frac{1}{2}$-inch T-bar frame members. The cutting plate (14 inches by $\frac{3}{4}$ inch) on the shore side is carried inside the skin-plate to ensure perfect contact with the ground, and to guard against any draw from the direction of the wall. All rivets are $\frac{7}{8}$ inch in diameter and countersunk on the skin. The dimensions of the working chamber, allowing for the overhang of the walls, were 17 feet by 6 feet 3 inches by 6 feet 6 inches, with a 5-foot by 3-foot 6-inch shaft moulded in the concrete fill connecting with the compressed-air shaft and lock.

For handling and positioning the caissons a timber staging, supported on piles (with toe-level − 30·00 O.D.), was constructed on the line of the work and laid out to give a clear opening at the site of each caisson (*Fig. 4*, facing p. 13). On it at stage-level + 16·00 O.D. and bearing on joist members bridging the openings, the shell-steel was assembled and riveted up, and carefully checked for position on completion. After erection, the reinforcing steel, which is bonded to that in the piers, was set and the shell concreted up, with the exception of the shaft leading to the working chamber.

Around the loaded caisson, which weighed 250 tons and was supported on the piling, a steel stallage, 30 feet in height, was built. Four hydraulic jacks were fitted at the top of this frame and housed between girders, whilst between the twin webs of the girders built-up steel straps were attached to eyes fitted on the caisson sides, so that, when lowering the mass, the weight was first taken by the lower girders through pins inserted through the webs and straps, and then the jack-head connected to the top girder was extended. When further pins were inserted through that

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Fig. 3.

GENERAL VIEW OF POWER-STATION AND COALING JETTY.

Fig. 4.

STAGING, STEEL STALLAGE, AND CAISSON-LOWERING GEAR.

girder, the lower pins were withdrawn, and the whole weight was under control of the jacks. This arrangement worked so well that in the fourteen caissons sunk the greatest divergence for line and level did not exceed $1\frac{1}{2}$ inch.

During sinking operations the period of control by the jacks varied with the nature of the ground, the general procedure being to lower the caisson 2 to 3 feet into the shore-bed (+ 2·00 O.D.), when the shaft and lock were fitted. The compressed air was then turned into the workings, and excavation commenced in short depths, the men being withdrawn during the stage of "blowing down" and lowering. This method continued through the muds and ballast until the cutting edge was well bedded in firm clay, when the control was removed, and sinking continued under the caisson's own weight to a final level of – 20·00 O.D. There were several sites where the caisson was lowered into extremely soft ground of muds and peats without any trace of ballast, and had it not been for the control a heavy lurch towards the river must have occurred and been most difficult to correct.

Working pressures, varying with the tide, ranged between 5 and 10 lb. per square inch, but during concreting the working chamber it was increased to 15 lb. per square inch to prevent settlement. Working night and day in 12-hour shifts, the average time to assemble, load and sink a caisson was 1 week.

Piers and Superstructure.

The piers, at 22-foot 8-inch centres, are in reinforced concrete, the reinforcement bonding with the crane girders and being carried down just short of cutting-edge level. From apron-level (at Ordnance datum) at the caisson-top to 2 feet above high tide (+ 16·50 O.D.), the piers are protected by a casing built up in cast-iron segmental rings, 6 feet in diameter and 3 feet 9 inches in depth, with the 4-inch flange lead-caulked and the $\frac{3}{4}$-inch diameter bolts grummeted.

The construction of the piers was carried out in the following manner:— the cast-iron cylinders, 18 feet 9 inches in height, were assembled and caulked on shore, and lowered at low tide into the recess cast at the caisson-tops; after having been set for line and verticality, the portion of the recess external to the cylinder was concreted with a rapid-setting mixture, thus allowing the caulking to be tested during the next tide; the pre-assembled reinforcement was then lowered into the cylinder, the bond with the steel projecting from the caisson made good, and the whole concreted up within a few inches of casing-top.

The superstructure, 350 feet in overall length by 35 feet in width, is of reinforced-concrete design consisting of thirteen spans with crane-girders, 4 feet in depth, set at 22-foot 8-inch centres, and capable of supporting a wheel load of 40 tons at 6-foot centres. In parallel with these girders are subsidiary beams at 5-foot 6-inch centres and 2 feet in depth, carrying the

8-inch-thick deck (level + 24·50 O.D.). In addition to their other duties the 4-foot-deep portal beams take the load of a coal-conveying gantry 18 feet in width and constructed in reinforced concrete, with a deck-level of + 35·33 O.D., the gantry being straddled by the cranes and hoppers feeding to the belt conveyor.

Access to the jetty is provided by a reinforced-concrete bridge, 10 feet in width, spanning the 25-foot-wide barge-berth; the design is such that the river end of the bridge is built into the fascia beams, whilst the shore end has its bearing on gun-metal plates supported by raking piles cast on site. This has been done to relieve any shock of impact of a vessel berthing at the jetty.

Fenders.

The main fenders are positioned on the centre line of the riverward piers. Each fender is a cluster of eight 14-inch by 14-inch creosoted Douglas fir piles, 46 feet 6 inches in length, with toe level (— 24·00 O.D.) 4 feet below the bottom of the caisson and with the whole cluster finally bolted together through its 4-foot 8-inch width.

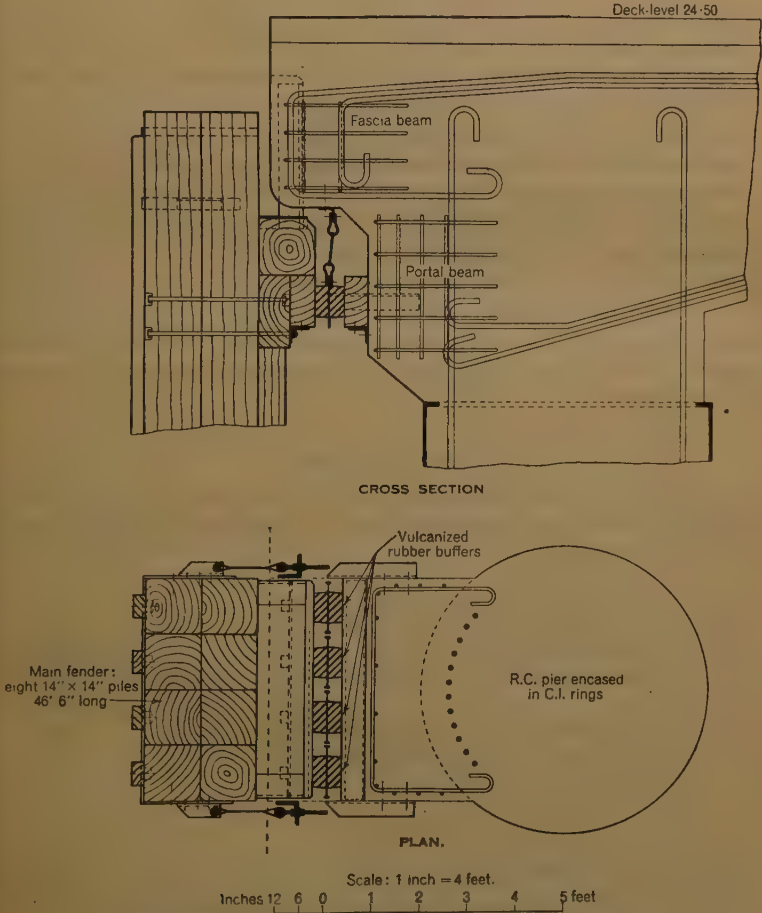
At apron-level, and partially surrounding the pier, is constructed a reinforced-concrete buffer-block (*Figs. 5*) with its steel bonded well into the concrete fill of the caisson. Through the end of the block pass bolts securing two stout timber jaws giving lateral support to the fender from that point to dredging level (— 12·0 O.D.). The fender is stiffened at the back by timber diagonal and horizontal bracings, and is provided with hardwood rubbing pieces.

The arrangement for absorbing a reasonable shock imparted to the fender during mooring a vessel is arranged in the following manner:— beneath the fascia beam, which projects over the end of the portal beam by 2 feet, four vulcanized rubber buffers, 8½ inches in diameter with a maximum thickness at their centre of 7½ inches, are suspended independently and in line; each buffer is mounted in a thin bronze frame with an even protuberance at each side, and the frames are prevented from moving sideways by angle-iron jaws projecting from the portal beam.

Previous examination by experiment showed that a buffer under a compression of 4 inches registered a load of 20 tons. There is a 4-inch clearance between the back of the fender-top and the fascia-beam, and contact is made to either side of the buffer by measured hardwood packs cleated on to the fender-back and the portal-beam. There are also screw attachments from the fender-top to the fascia-beam. In order to lessen the impact of a blow, the screw attachment is tightened 1 inch, reducing the clearance at the fender-top to 3 inches, and also giving a permanent compression of 1 inch on the buffer. On a further compression of 3 inches due to the impact of a vessel, the fender-top makes contact with the jetty so that a blow exceeding that of 80 tons taken up by the buffers is transmitted to the jetty structure.

There are subsidiary fenders surrounding the jetty and extending down to apron-level, whilst from that level the ground between the caissons is supported by reinforced-concrete camp sheet-piling which is continued at both ends on the rear line of the jetty in support of the barge-bed.

Figs. 5.



DETAILS OF MAIN FENDERS AND SHOCK-ABSORBERS.

Dolphins.

A timber dolphin, triangular in plan, 38 feet long by 35 feet wide with a deck-level of + 24·5 O.D., is provided at 35 feet from each end of the coaling jetty. The two dolphins are constructed of 12-inch-square Douglas fir piles driven to a toe-level of — 24 O.D. and braced horizontally and diagonally against shock from the direction of the stem; the whole

structure is girdled by a 14-inch-square floating boom, which finds a seating on angle-iron cleats 4 feet above low tide. All timbers were incised before being creosoted under a pressure of 180 lb. per square inch and an oil-temperature of 150° F. Steel gangways connect the decks of the dolphins to the jetty.

Dredging.

The general level of the shore on the jetty frontage was + 2·0 O.D., sloping down to the fairway 100 yards out with levels — 12·0 O.D. at the edge and — 15·0 O.D. at the centre. The length of the deep-water basin in front of the jetty to enable the colliers to berth with ease is 250 yards, and the basin is dredged to the level of the channel edge (— 12·0 O.D.).

Dredging started from the downstream end of the basin with the final cut entirely in stiff clay. Difficulty was experienced throughout the work by the continual deposit of silt over the new work due to the site being on the inside of the river bend from Wandsworth bridge to the Shell Mex wharf, ½ mile downstream. Further dredging took place in making a channel 50 yards wide between the fairway and the entrance to the intake-chamber (— 14·5 O.D.). Here, again, silt was a continual source of trouble and maintenance.

Cost of Works.

The costs of the various sections of the constructional works described above are given in the following Table, together with the names of the Contractors concerned :—

	£
Preliminary excavation (E. D. Winn and Co., Ltd.)	13,365
Retaining walls and raft (Sir William Prescott and Sons, Ltd.) .	118,719
River-wall and coaling jetty (Peter Lind and Co., Ltd.) . . .	65,726
Circulating-water chambers and tunnels (Charles Brand and Son, Ltd.)	156,091
Dredging (The Tilbury Contracting and Dredging Co., Ltd.) . .	13,184
Dredging (Portion of the work carried out by the Port of London Authority)	11,708
Total	£378,793

The Joint Consulting Engineers for the construction of the new power-station were Messrs. Preece, Cardew & Rider and Mr. Arthur J. Fuller, who appointed Sir Harley Dalrymple-Hay and Messrs. Mott, Hay and Anderson, MM. Inst. C.E., as joint Civil Engineers for the works dealt with in this Paper. The latter took charge of the design and construction of the work, the Author acting under them as Resident Engineer.

The Paper is accompanied by three tracings and two photographs, from which the Figures in the text and the half-tone page-plate have been prepared.

Paper No. 5171.

"Fulham Base-Load Power-Station: Mechanical and Electrical Considerations." †

By William Clifford Parker, A.M.I.E.E., and Hubert Clarke, A.M.I.Mech.E.

TABLE OF CONTENTS.

Introduction.

When finally completed, the new Fulham power-station will have a capacity of 310,000 kilowatts or more, and will be the largest municipally-owned base-load station in the British Isles. It stands on the north bank of the river Thames, the site covering an area of approximately 12½ acres and having a frontage to the river of 1,300 feet.

The decision to build the new station was the subject of an agreement with the Central Electricity Board, dated the 3rd August, 1929. Prior to the building of the station, the Council's proposals were advertised and an inquiry was held in December, 1930. Considerable opposition was

† Correspondence on this Paper can be accepted until the 1st September, 1938.—Sec. Inst. C.E.

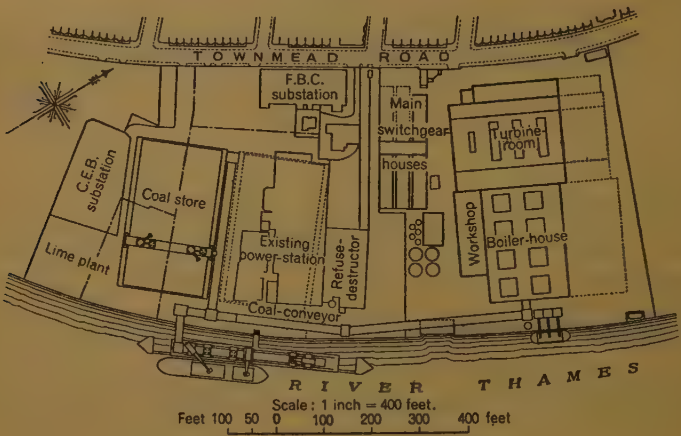
raised, being based almost entirely upon the risks of nuisance and possible damage to health and buildings from the emission of sulphur fumes and dust. For that reason, an efficient means of sulphur-extraction from flue-gases had to be employed. As there are only three such plants in operation, the Authors propose to devote special attention to the method and to the results obtained.

Work was commenced on clearing the site in July, 1932, and the opening ceremony of the first section took place on the 26th September, 1936.

General Layout.

The building consists essentially of a steel-framed structure, with steel stanchions carried upon a heavy concrete raft laid upon the London clay. The walls of the superstructure are of London stock bricks, filling the

Fig. 6.



Layout of Station.

spaces between the main stanchions, carried upon steel beams at intervals, with horizontal stone bands to provide relief. The present two chimneys are of reinforced concrete and rise to a height of 300 feet above ground-level.

The general layout is shown in *Fig. 6.* The work included in the first section is shown in full lines, and the remainder, which has yet to be carried out, in dotted lines. Site-conditions necessitated the turbines being positioned transversely across the turbine-room, with boiler-houses lying at right angles. The locations of the switch-houses and control-room, whilst to some extent determined by site-conditions, were governed principally by the consideration that it was essential in modern design, with high rupturing capacities and large oil-quantities, to isolate the switchgear from the main building as effectively as possible; for this reason the switch-houses are entirely separate buildings. Further, each section of

switchgear is housed in a separate switch-house, so as to localize the results of fire or explosion to one group of feeder or alternator switches.

Coal-Supply.

Coaling System.

The transport, storing and handling of coal is too large a subject to be dealt with in this Paper. Subsidiary notes have therefore been made on this question, and will be filed with the manuscript of the Paper.[1] Sea-going colliers are employed for bringing coal to the power-station; the coal is unloaded at the jetty and handled by conveyors to the silo and bunkers.

Quality of Coal Required.

The type of coal used is controlled in the main by the requirements of the stokers and conveyors. Good buying depends on having as wide a specification as possible, and experiments on sizing have shown that coal could be used with up to 40 per cent. passing through a ⅛-inch mesh, providing that the moisture-content did not exceed 12 per cent. Alternatively, if there were more than 40 per cent. over ¼ inch, the size of the remaining coal was immaterial and the moisture-content could be allowed to go to 15 per cent. These figures, however, are the limits, and it is found that shoots are particularly liable to become choked if the limits are exceeded by only a small margin.

Experience appeared to show that many collieries had very little accurate conception of the sizing figures for their coal and were unaware of the tremendous variations which took place from cargo to cargo. It therefore became essential to include in the coal-specification sizing figures to be guaranteed by the coal-contractor. It is gratifying now to find that the main collieries are able to give consistent deliveries. All coal is bought on analysis and subject to penalties where guaranteed figures are not obtained, after allowing suitable tolerances. This involves constant sampling and testing of all coal received.

A point which has become apparent, due to the building in recent years of base-load stations, is the extreme desirability of being able to utilize coals of widely-varying characteristics. At least two base-load stations on the river Thames are equipped with the same type of stoker and similar methods of feeding, with the result that these stations are purchasing coals having similar characteristics. This is bringing about an increased demand on the coalfields for a narrow range of their product, thus tending not only to increase the price, but also to bring about a shortage of that type of coal. In the design of power-stations, therefore, it appears desirable to consider carefully not only the type of stoker, but the design of all

[1] These may be seen in the Institution Library.—Sec. Inst. C.E.

conveying equipment, so as to widen as far as possible the range of sizing of the coal which can be utilized.

Structural and Building Features.

The buildings of the power-station, the layout of which is shown in *Fig. 7*, were designed to meet fully the requirements of the London County Council Special Building Regulations.

The whole of the structure is carried on a heavy concrete raft laid on London blue clay at a depth of about 30 feet below ground-level, and the stanchion-loads are distributed by means of steel grillages so that the pressure on the clay does not exceed 4 tons per square foot.

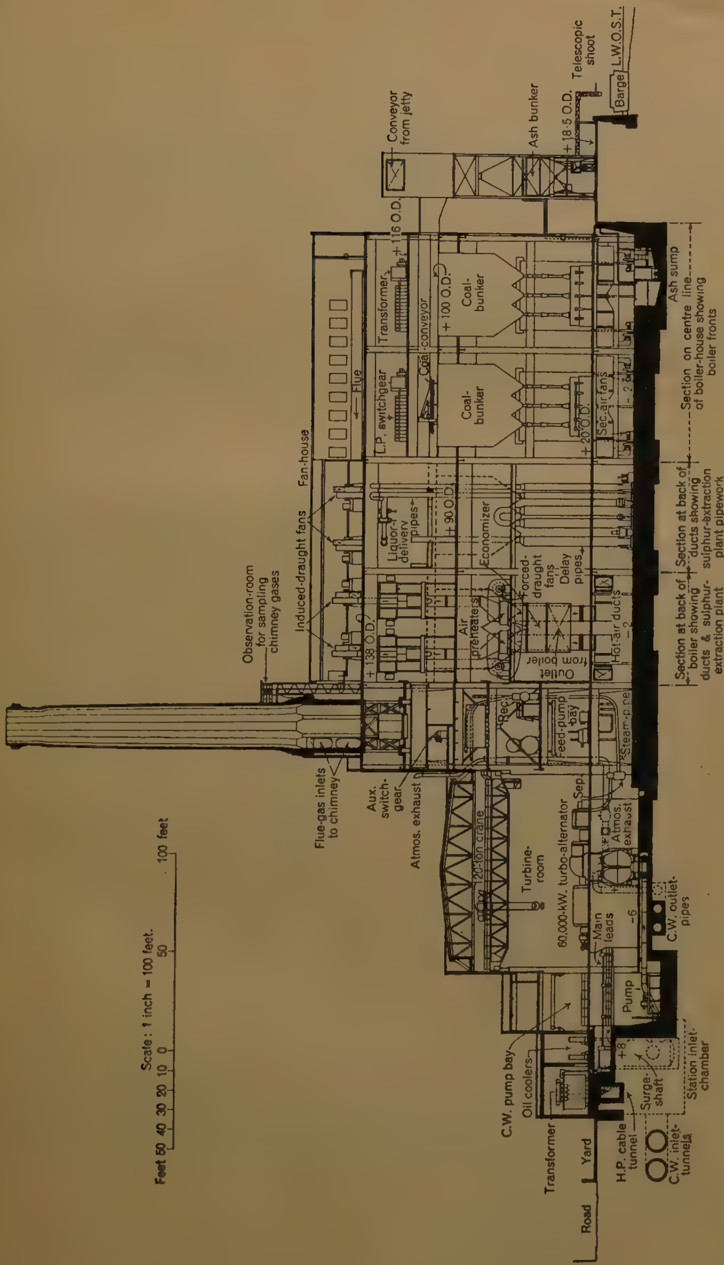
Allowance was made for wind-pressures of 15 lb. per square foot on the main building, and 25 lb. per square foot on the projected area of the chimneys and on all projections above the main roof. In designing the structure for wind-loading it was assumed that the wind-forces acting on the east end of the boiler-house would be transferred as direct thrust through the girders at floor-levels to the feed-pump bay, which is braced in both directions to transfer those forces to the foundations. Similarly, forces on the circulating-water pump bay and the west side of the turbine-room were transferred to the feed-pump bay through the turbine-room roof-trusses. To resist wind on the north and south faces of the building each line of stanchions was designed to take up its proportion of the wind-moment.

The total weight of structural steelwork in the frame is about 21,000 tons.

Boiler-House.

The boilers are carried on self-supporting structures built up from the basement, but the gas-washing plant, fans, and other auxiliaries are carried on the main structure, which is composed of stanchions and main girders built up of plate and angle sections. As will be seen from *Fig. 7*, four coal-bunkers are provided, each of 800 tons capacity and feeding coal to two boilers. The bunkers are of all-steel construction, and are carried by means of hangers from the main girders; in order to avoid carrying heavy loading by means of rivets in tension, the lower flanges of the main girders are split and the hangers taken up into the girder section. The main girders consist of members 55 feet by 10 feet by 2·5 feet spanning between cruciform stanchions, and in the design of these stanchions it was found that the eccentricity of the main girders was such that a very large moment was developed when one bunker was full and the next one empty. In order to limit this moment, part of the stanchion section was capped at the underside of the girder and the girder was carried on a rocker bearing. The main bunker girders are located at approximately + 90 O.D., and thus

Fig. 7.



General Section through Station.

form a main connexion for the gas-washer floor steelwork. The bunkers are lined with a 3-inch layer of "Gunite."

Feed-Pump Bay.

This bay takes up wind-pressures, both from the main buildings' superstructure and from the chimneys. As conditions of plant layout would only permit of cross bracing in one section of the bay, the remaining sections have been braced with portals in both directions. It is of interest to note that the lower length of the heaviest stanchion is designed to transmit a load of about 2,700 tons.

Each chimney-structure is supported on an octagonally-braced framework, which is carried on a system of twin plate girders arranged so that the weight of each chimney is spread over six main stanchions.

Chimneys.

The two chimneys are of reinforced-concrete construction, rising to a height of 300 feet above ground-level. The internal diameter of each is 21 feet 6 inches at the base and 17 feet 9 inches at the top. The wall-thickness above the bottom plinth is 12 inches, tapering to 7½ inches at the top, the weight of each chimney being approximately 800 tons.

In view of the saturated state of the gases entering the chimney, together with a slight amount of residual sulphur oxides, protection had to be provided to prevent chemical attack of the concrete and finally of the reinforcement. During the preparation of the design there was some fear that the temperature of the gases after leaving the washer would be such as to call for reheating to guard against inversion of temperature. For this reason reheating chambers were installed at the base of the chimney. Practice has shown, however, that these are not required.

On the east side of each chimney shaft an observation-room has been arranged for gas-sampling purposes, and accommodates continuous sulphur-recording apparatus.

Turbine-Room.

The turbine-room, being 105 feet wide, has necessitated careful design of the roof-members, which are of modified warren-girder type. The main generating units are laid out at 48-foot centres and lie transversely across the turbine-room, the house machine being located south of the main generating units.

The main circulating-water pipework to and from the condensing plant is built into the basement-raft.

Steam-Raising Plant.

Boiler-Units.

The steam-raising plant comprises eight boiler-units, each consisting of a Stirling tri-drum boiler fired by a retort-type stoker, with economizer and regenerative air-heater, to ensure maximum thermal efficiency. Fig. 8, Plate 1, gives a cross section of one boiler-unit.

The main technical particulars of the various parts of the unit are given in Table I.

Table I.

Grate-area	708 square feet.
Combustion-chamber volume	13,500 cubic feet.
Total heating surface :—	
Combustion-chamber	2,067 square feet.
Boiler	22,680 ,, ,,
Superheater	9,600 ,, ,,
Economizer	14,700 ,, ,,
Preheater	36,200 ,, ,,
Each of the units works to the following conditions at maximum continuous rating :—	
Evaporation	260,000 lb. per hour.
Superheater-outlet pressure	625 lb. per square inch.
Final steam-temperature	850° F.
Feed to economizer	350° F.
Total heat in steam above feed	1,118·0 B.Th.U. per lb.
CO_2 in furnace	15·0 per cent.
CO_2 in air-heater outlet	12·75 ,, ,,
Gas-temperature leaving furnace	2,240° F.
,, ,, to superheater	1,750° F.
,, ,, to rear bank	1,100° F.
,, ,, to economizer	740° F.
,, ,, to air-heater	510° F.
,, ,, leaving air-heater	240° F.
Air-temperature entering heater	60–85° F.
,, ,, leaving heater	400–350° F.
,, pressure under grate	1·0 inch of water.
,, ,, entering heater	3·4 ,, ,,
Water-temperature entering economizer	350° F.
,, ,, leaving economizer	425° F.
Coal fired per hour at approximately 10,900 B.Th.U. per lb.	31,050 lb.
Volume of flue-gas at air-heater outlet	120,100 cubic feet per minute.
Volume of air required at preheater inlet	74,000 ,, ,, ,,
Heat liberated per hour per cubic foot of combustion space	25,000 B.Th.U.
The approximate distribution of heat-transfer in the boiler is equivalent to the following steam-generation :—	
Water walls	118,500 lb. per hour.
Front bank	123,000 ,, ,, ,,
Rear bank	18,500 ,, ,, ,,
	260,000

The eight mechanical stokers in the station are of the retort type, comprising eighteen retorts, having a width between side-walls at the stoker level of 31 feet 5½ inches. The stoker operates on the underfeed principle, the retorts and tuyere-banks being arranged alternately across the width of the grate. The length of each retort is about 15 feet and the fuel rises from the whole length, meeting across the tops of the intermediate tuyere-banks so that a continuous and large underfeeding fuel-bed is thus formed from one side of the furnace to the other.

A short extension-grate occurs at the end of the retort and tuyere-bank section, from which the residue of combustion is passed rearward to a crusher-pit containing two large rotary ash-discharge rolls at the lower end. These rolls are provided with crusher-teeth, and are caused to rotate outwardly and in opposite directions, thereby crushing the refuse against adjustable aprons and discharging it to the ash-hoppers and sluices below. The rate of discharge is arranged so that in normal operation the pits are always full, and they are arranged and proportioned so that the refuse is continually scrubbed by a flow of low-velocity air for a period of about 12 hours before being discharged by the rolls; it has been found that the carbon-content of the resultant ash is thereby reduced to about 5 per cent.

One of the additional advantages of the crusher-pit is that the grate-surface proper is relieved of the duty of removing the last stages of carbon from the residue of combustion, and that it can thus be entirely utilized for its main function of coal-burning, so that the average air-velocity through the fire is relatively low and a high combustion-rating can be efficiently obtained in the available furnace-area.

Since the commencement of the operation of the station, coals from the Welsh, Northumberland, Durham, and Scottish fields whose characteristics fall within the following limits have been satisfactorily used :—

Volatile	13·4 to 31·3	per cent.
Fixed carbon	76·0 to 45·9	,, ,,
Ash	11·3 to 4·1	,, ,,
Moisture	4·4 to 17·7	,, ,,
Calorific value as fired . . .	14,070 to 10,960	B.Th.U. per lb.

Table II gives constructional particulars of the boiler proper.

All the drums are manufactured from solid steel forgings, and are designed for a working pressure of 800 lb. per square inch.

Possibly the most interesting feature of the boiler-unit is the superheater-installation. The design stipulated that the final steam-temperature was to be 850° F., and that the variations in temperature between evaporations of 150,000 lb. per hour and 260,000 lb. per hour were not to be greater than 20° F.; further, that the final steam-temperature between loads of 200,000 lb. per hour and 260,000 lb. per hour was to be as uniform as possible. It is, of course, impossible to obtain such a superheater-performance with the usual convection-superheater or a combination of convection- and radiant-superheaters, so that some form of steam-tempera-

ture control had to be included in the superheater-design. This was achieved by dividing the convection-superheater into two sections, which were termed primary and secondary superheaters, and further arranging for a de-superheater system to be interposed between these two superheaters. The necessary ideal heating surface, 9,600 square feet, was installed in order to give the specified performance at the lowest rating under consideration, 150,000 lb. per hour. When the heat added to the

TABLE II.

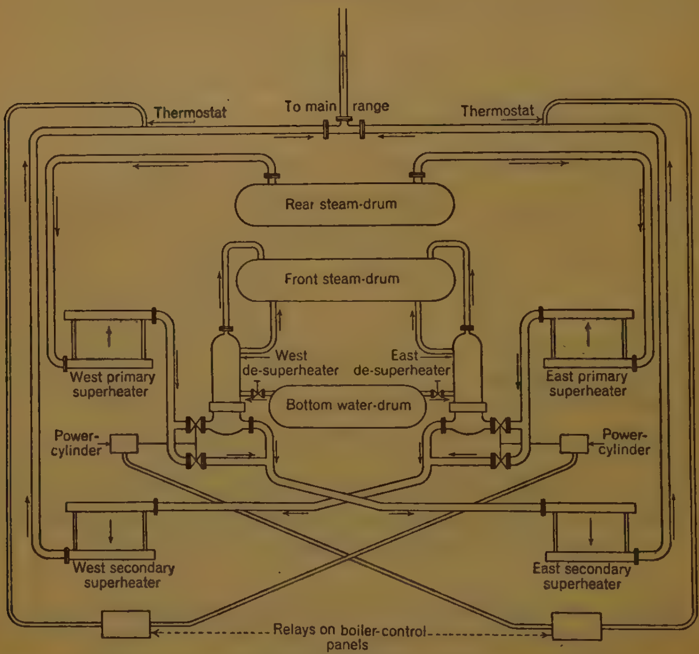
Front steam drum, internal diameter	3 feet 6 inches.
,, ,, ,, thickness	$3\frac{1}{8}$,,
,, ,, ,, length over cylindrical portion	37 ,, 3 ,,
,, ,, ,, ,, ,, ends	39 ,, 7 ,,
,, ,, ,, approximate weight	28 tons.
Rear steam drum, internal diameter	4 feet 6 inches.
,, ,, ,, thickness	$4\frac{3}{8}$,,
,, ,, ,, length over cylindrical portion	37 ,, 3 ,,
,, ,, ,, ,, ,, ends	40 ,, 8 ,,
,, ,, ,, approximate weight	52 tons.
Mud-drum, internal diameter	4 feet 6 inches.
,, ,, thickness	$3\frac{7}{8}$,,
,, ,, length over cylindrical portion	33 ,, 6 ,,
,, ,, ,, ,, ends	36 ,, 11 ,,
Number of main tubes	1,139
,, ,, cross tubes	130
Thickness of first two rows	4 gauge (0·232 inch).
,, ,, remaining tubes	5 ,, (0·212 ,,).
Outside diameter of tubes	$3\frac{1}{4}$ inches.

steam by the superheater is in excess of that required to give the steam-temperature of 850° F. at the superheater-outlet, a suitable proportion of the steam generated is cooled by being passed through the de-superheater.

During the progress of detailed design it was decided to provide two separate superheaters, each consisting of a primary and secondary section, and each superheater being provided with its own intermediate de-superheater. The arrangement is shown in *Fig. 9* (p. 26). It was realized that considerable differences might occur between the temperatures of the steam leaving the two superheaters, owing to such causes as uneven firing or stratification of gases. To minimize this effect the connexions were so arranged that the steam from the left-hand primary superheater was caused to flow through the right-hand secondary superheater, and vice versa. The two primary superheaters were located side by side in the boiler, occupying its full width, and immediately in front of them were placed the two secondary superheaters. The regulation of the steam-temperature is carried out by the simultaneous adjustment of two thermostatically-controlled butterfly valves, one located in the de-superheater by-pass circuit and the other in the de-superheater circuit.

The proportion of steam to be de-superheated enters the base of the de-superheater body and flows through U-shaped tubes in that vessel, which are surrounded by water fed from the boiler circuit, thus cooling the steam and converting the superheat into latent heat, the steam generated being returned to the steam space of the front drum of the boiler. To maintain a circulation and prevent concentration in the de-superheater vessel, a further connexion is taken from below the water-level in the de-superheater vessel to the boiler circuit. It will be seen

Fig. 9.



CONNEXIONS OF SUPERHEATERS AND DE-SUPERHEATERS OF ONE STEAM-UNIT.

that the two de-superheaters are located immediately in front of the boiler and so arranged that the water-level in the de-superheater vessel corresponds to that existing in the boiler-drums.

Each of the boilers is fitted with a gilled-tube economizer, between which and the boiler two feed-water regulators are installed. Adequate arrangements are also made to continue feeding the boiler directly from the feed-main. Immediately above the economizer on each boiler are two rotary air-heaters.

About 1·4 ton of ash has to be removed from each boiler per hour; this is sluiced away by means of a high-pressure jet system and discharged into a central sump, from which it is lifted by special ash-handling pumps

and deposited in raised hoppers ready for loading into trucks or barges. The hoppers are arranged for quick draining, the water drained therefrom returning to the central sump.

Boiler-House Auxiliaries.

Adjacent to the boiler-house is a separate boiler-house control-room, which has been designed to have available continuously all the information required to enable instant and continuous checks to be made on the performance of the boiler-plant.

The boiler-house auxiliaries are supplied from the main auxiliary feed brought in to a switch-room at 6,600 volts between phases, and there transformed down to 400 volts by eight air-blast-cooled transformers of 950 kilovolt-amperes each.

Fans.

Two induced-draught fans are provided for each boiler; they are inserted between the outlet of the sulphur-extraction plant and the ducts to the chimneys, and are driven by two-speed electric motors.

The fans are designed to be self-cleaning. This is necessary because they follow immediately after the gas-washing plant and are therefore subjected to a carry-over of fine wet particles, consisting of calcium sulphate or sulphite together with very minute particles of grit, which tends to adhere to the runners, thus bringing about out-of-balance. To overcome this difficulty, jets and sprays are installed within the fan-casing to play on the runners and to keep them swept with a film of moisture, to enable all solids to be washed off. In practice it has been found very difficult to obtain a complete cleaning of the runners, and out-of-balance does occur after a fair amount of continuous running. Further, it is found that the carry-over from the washers has both an erosive and corrosive action on the runners and on the sprays and nozzles within the casing. At the present time experiments are being carried out with a rubber-covered runner, with a view to overcoming this difficulty. Rubber covering can be done in a number of ways, and the normal methods which have been available in the past are certainly not suitable for this particular type of work. Experiments are now being carried out on a new method of attaching the rubber to the metal, and it is hoped that the necessary adhesion will be obtained.

Each boiler is provided with two forced-draught fans, again driven by two-speed motors, the output at either speed being controlled by the use of movable vanes.

Two electrically-driven secondary-air fans are also provided for each boiler. At one time there was considerable discussion as to their necessity or otherwise, but practice has shown that with certain types of fuel (particularly Scottish coal) secondary fans are essential for proper combustion-conditions.

Boiler Control-Panels.

Each boiler is provided with its own control-panel, which gives full and centralized control for the operation of the boiler.

Stoker-Drive.

The recent considerable increase in the size of mechanical stokers has created a demand for a drive able to deal satisfactorily with exacting load and speed requirements. These requirements have been satisfactorily met in the Fulham station by the use of an hydraulic variable-speed transmission between the prime mover and the stoker. The gear employed is a development of the original "Williams-Janney" gear, and consists of a variable-delivery pump driven at a constant speed by a squirrel-cage electric motor and supplying fluid to a hydraulic motor which drives the stoker. Thus, by suitably controlling the delivery of the pump, the stoker may be driven at any speed from zero to maximum.

GAS-WASHING PLANT.

General Considerations.

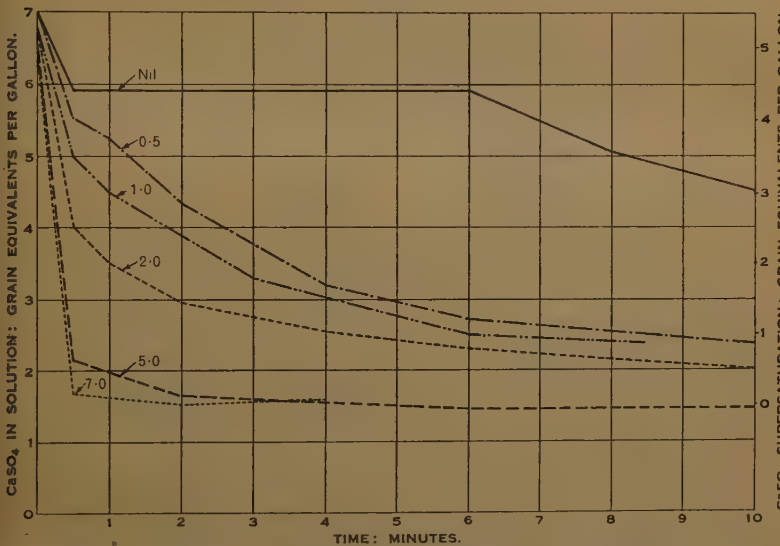
Government and public interest in the emission of sulphur dioxide from power-stations has grown with the increase in the coal-consumption of individual stations, which has been considerable since the War. The matter has been deemed so important by the health authorities that in 1927 sanction to build the first portion of a London base-load station was only obtained on the condition that the best practicable sulphur-extraction plant was to be incorporated. For the building of the Fulham power-station similar restrictions were imposed, but with one essential difference, namely, that definite limits were laid down, the gases leaving the chimneys being required to contain not more than 0·03 grain of sulphur per cubic foot.

In any gas-washing scheme yet conceived for the removal of sulphur, some form of alkali has to be used and some solid residue will be produced. In existing practice that residue is in the form of calcium sulphate or calcium sulphite. The alkalis required for the process exist in river-water, and if sufficient river-water is used they can be obtained free. Unfortunately, however, in the case of the Fulham station, there is not always enough water available from the river Thames to allow this to be done. Moreover, the effluent produced could not be discharged into the river, as, in the present state of the art, it would be impossible to guarantee that practically no reducing matter would enter the river, as stipulated by the river authorities. Clearly, therefore, as far as future power-stations on the river Thames are concerned, a non-effluent system will have to be adopted.

On this basis experiments were started at the old Fulham power-station on flue-gases from one boiler, this boiler having an evaporative capacity

of 40,000 lb. per hour. The experiments were carried out on the principle of passing water, containing various forms of lime and other forms of alkali, in thin films at right angles to the gas flow. The sulphur dioxide in the flue-gases was neutralized by the lime and precipitated as a mixture of calcium sulphite and calcium sulphate, the proportion of sulphate to sulphite depending upon the amount of oxidation which took place in the process. These experiments proved at a very early stage that the main problem was to prevent choking by crystallization of the calcium sulphate formed at concentrations greater than saturation. This was achieved by maintaining a suspension of calcium sulphate crystals in the

Fig. 10.



EFFECT OF SUSPENDING VARIOUS PERCENTAGES OF $CaSO_4.2H_2O$ UPON THE SOLUBILITY OF $CaSO_4$ AT 50° C.

washing medium so as to de-supersaturate the solution in portions of the plant specially designed for the purpose. In this connexion a tribute has to be paid to Dr. Rudolph Lessing for the pioneer work done by him in these early and important experiments.

Curves showing the result of his work in connexion with de-supersaturation are given in *Fig. 10.* The curves show the rate of de-supersaturation of calcium sulphate solutions by the addition of various percentages of gypsum crystals. The total amounts of calcium sulphate dissolved in the mother liquor are marked on the left of the diagram, and times are marked on the base of the diagram. On the right are indicated the amounts of supersaturation of the mother liquor with respect to calcium sulphate. All units for solubility or supersaturation are in grain-equiva-

lents per gallon. One grain-equivalent per gallon is equal to 66 grains per gallon (approximately 95 lb. of $CaSO_4$ per 100,000 lb. of solution). Thus at saturation-point at 50° C., according to the diagram, 1·5 grain-equivalents of calcium sulphate are dissolved in one gallon of liquid (142 lb. per 100,000 lb.). It will be observed that when more than 5 per

Fig. 11.

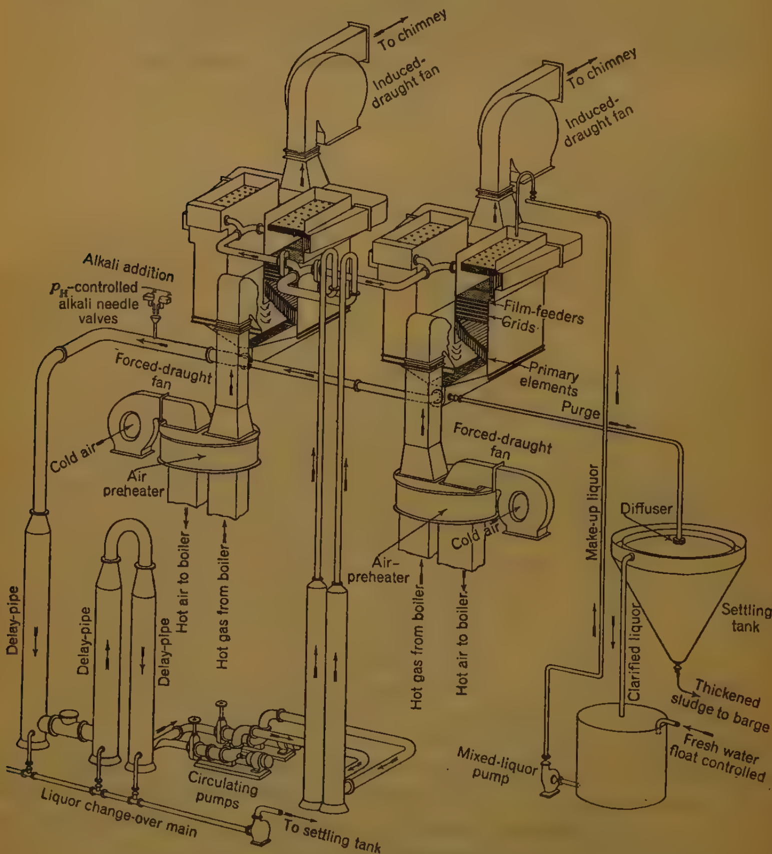


DIAGRAM OF OPERATION OF SULPHUR-EXTRACTION PLANT.

cent. of gypsum crystals is suspended in a liquor, which commences in a highly supersaturated state, within 1 minute the supersaturation falls almost to nothing, whereas in the presence of smaller quantities of gypsum supersaturation persists to a marked extent for more than 10 minutes. In practice a delay-period of $3\frac{1}{2}$ minutes is allowed between cycles of the recirculating liquor, so that the presence of 5 per cent. or more of gypsum

suspended in the circulating liquor effectively prevents any supersaturation existing in the liquor entering the washer-packing. Without this precaution, owing to the high capacity of calcium sulphate for forming supersaturated solutions, the working liquor would be highly supersaturated and would be liable to deposit crystals of gypsum in the packing, speedily leading to the failure of the washer by choking.

In practice the successful non-effluent system carries in the circulating liquor substantial amounts of washer-solids containing large numbers of seeding crystals, which accelerate precipitation of the calcium sulphate formed during each cycle. The liquor becomes slightly supersaturated during its passage through the scrubbers and becomes de-supersaturated before being returned, without the necessity for the introduction of a very large liquor-capacity in the circulating system.

At the same time as these experiments were going on, Imperial Chemical Industries, Ltd., were working on parallel lines,[1] and the plant now installed at Fulham is the result. An isometric diagram showing the principle of the sulphur-extraction plant is shown in *Fig. 11.*

Particulars of Design.

The design figures appertaining to the plant associated with one boiler are given in Table III (p. 32).

The boiler operating-conditions, to which the sulphur-extraction plant was designed, were as given in Table IV (p. 32).

These represent the extreme conditions anticipated, and any improvement in firing conditions obtained by the use of coal having a higher calorific value or a lower sulphur-content will ease considerably the duty and the cost of running of the sulphur-extraction plant. In operation, therefore, every endeavour is made to utilize coal with a high calorific value and a sulphur-content of about 1 per cent.

The physical layout of the sulphur-extraction plant is shown in Fig. 12, Plate 1.

Operating Experience.

It can first of all be said that the efficiency of the plant is beyond dispute, and the actual sulphur-content in the exit-gases, instead of the permitted figure of 0·03 grain of sulphur per cubic foot, is generally as low as 0·006 grain of sulphur per cubic foot, while only mere traces of dust having a size less than 5 microns pass out with the exit-gases to the atmosphere. The behaviour of the plant is thus excellent for the purpose for which it was installed. As was to be expected, however, with plant of a completely

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[1] J. L. Pearson, G. Nonhebel, and P. H. N. Ulander, "The Removal of Smoke and Acid Constituents from Flue Gas by a Non-Effluent Water Process." Journal Inst. Fuel, vol. viii (1934–35), p. 119. (*This Paper also appears in* Journal Inst. E.E., vol. 77 (1935), p. 1.)

new design, a number of difficulties have been experienced in operation, but they are confined to the maintenance of the plant. In this connexion it may be remarked that as modern boiler-house design progresses, so are more auxiliary pieces of apparatus brought into being, each of which adds to the possibility of interruption of service. Each individual part

TABLE III.

Weight of liquor in circulation	200 tons approx.
,, ,, ash and unburnt carbon caught in the plant	781 lb. per hour.
Solids formed, assuming 50 per cent. oxidation .	3,685 ,, ,, ,,
Total solids in suspension, with 5 per cent. suspended gypsum in recirculating liquor	13 per cent.
Rate of circulation of washing liquor	11,500 gallons per minute.
Temperature of flue-gases entering the plant . .	240° F.
,, ,, ,, leaving the plant . . .	124° F.
Humidity of gases leaving the washer	100 per cent.
Make-up water required	32·7 gallons per minute.
Rate of flow of liquor to the settling plant . . .	496 ,, ,, ,,
,, ,, ,, returned or clarified liquor from the settling plant	445 ,, ,, ,,
Complete weight of one unit in working order, exclusive of delay-pipes	300 tons.
Total cross-section of a washer	400 square feet.
Number of cells per boiler	16
Maximum permissible gas-flow through one scrubber at 240° F.	118,900 cubic feet per minute.
Total capacity of the delay-tanks	6,300 cubic feet.
Delay-period	3·5 minutes.
Final volume of gas per boiler leaving the washer at 124° F.	105,000 cubic feet per minute.
Lime requirements, assuming an excess of 10 per cent. and a purity of lime of 92 per cent. CaO . . .	1,100 lb. per hour.

TABLE IV.

Coal fired (calorific value approx. 10,900 B.Th.U. per lb.)	31,050 lb. per hour.
Gas circulated	118,900 cubic feet per minute.
Temperature of gas at plant inlet	240° F.
CO_2-content of gas	12·5 per cent.
Sulphur-content of coal	1·7 ,, ,,

must therefore maintain a very high standard of reliability, in order that the whole may have a reasonable running life without interruption. Some of the problems which have been dealt with and which may be of interest are described below.

Rubber Lining.—In various portions of the plant, to protect pipes, pumps, tanks, etc., from corrosion or erosion, rubber lining is employed. It has been found that the method of attaching the rubber lining to the metal is not entirely successful, and that the degree of success at present appears

to depend to a great extent on the skill of the workmen employed. Particular difficulty was experienced in the early days, when rubber was used for lining the casings and impellers of the pumps for recirculating the liquor; it was ultimately decided that rubber-covered impellers could not be used with success. When rubber covering was dispensed with, considerable corrosion and erosion of the impellers took place. This was to a large extent cured by employing shrouded impellers and impellers made of special chrome steel.

Scrubbers.—It is very interesting to note that the theory evolved and put into practice to prevent scaling has been completely successful, and practically no evidence of scaling is shown. Contrary to expectations, however, a certain amount of silting takes place, which shortens the running life of the washer. The Authors believe that this silting is caused by the unequal flow and distribution of both liquor and gas by the disposition, size and shape of the various types of packing, liquor-distributors and spray-eliminators in the washer. The high degree of operating efficiency indicated leaves some margin for re-arranging the disposition of these constituent parts, and considerable improvements have already been made in this respect. It is also evident that the material and design of the packings in the scrubbers can be improved upon to give greater life, as considerable damage occurs to these during cleaning operations. This problem is now in hand.

Corrosion.—In the early days the grid packings were reinforced by brass strips, and it was found that these brass strips were being attacked by dissolved oxygen in the liquor and that the dissolved zinc and copper acted as a catalyst to oxidation in the system, resulting in a solid product 100 per cent. oxidized, and operating in a vicious circle by maintaining oxidizing conditions. It was evident from the operation of these washers that 100 per cent. oxidation produced corrosion in various parts of the system, and particularly on the mild steel of the washer-tanks themselves. The elimination of the brass strips resulted in bringing the percentage oxidation down to 65 to 70 per cent., and this immediately reduced corrosion to about one-third of its original value. Further success has been obtained by introducing an organic inhibitor to prevent the calcium sulphite changing to calcium sulphate, the best yet found being molasses. The introduction of sodium silicate to the extent of 20 to 30 parts per million has also reduced corrosion, by forming a protective skin on the metal.

Many interesting tests are being carried out in connexion with corrosion, and, broadly speaking, in the particular conditions under review it has been found that austenitic alloys offer considerable resistance to corrosion.

In addition to the above, tests have been carried out showing that the contact between metals of different potential or areas of different potential on a metal surface will cause increased corrosion of the anode and confer protection upon the cathode. These contact-experiments were carried out as a result of phenomena observed in connexion with the re-

circulating pumps. Thick and irregular deposits were observed on the impellers of the pumps, consisting of copper along the lines of flow across the blades, and correspondingly deep grooves were formed parallel to the lines of copper where galvanic action had caused rapid solution of the chrome steel. This phenomenon is explained by the experiments mentioned, and has resulted in the elimination of brass and similar materials from the washer.

Testing of Flue-Gases.

The Ministry of Health requires constant tests to be made of the sulphur-content of the flue-gases, and the difficulty of doing this when working to as low a sulphur-content as 0·006 grain per cubic foot will be realized. No instrument existed which was capable of continuously recording such minute quantities, and in the early days the analysis of the gases was taken by the testing of bulk samples taken over 24 hours by suction through absorption-vessels. The gas was drawn out from the chimneys at sampling-points from specially-built chambers on the chimney-stacks.

Experiments have been continuously carried out during the last 12 months; a suitable instrument has now been produced which records the percentage of SO_2 in the chimney-gases continuously over the 24 hours, and it is hoped at a later date to give a complete description of this instrument.

The final test as to the efficiency of the sulphur-extraction plant was made by placing testing stations in various parts of London to indicate the effect of the operation of the Fulham power-station.

In order that there might be a basis for comparison, an investigation of atmospheric pollution was commenced in April, 1936. Consideration was given to the several methods in use for measuring atmospheric polution, and it was decided to concentrate upon the measurement of the active sulphur in the air by means of the lead-peroxide method developed by the Building Research Station and described in the 18th report of the Atmospheric Pollution Research Committee.[1] In brief, the method is to expose a prepared surface of lead peroxide to the atmosphere for a certain period and to estimate the lead sulphate resulting from the attack by oxides of sulphur. The results give a quantitative measure of activity, and are comparable for a given set of conditions. Following the advice given by the Chief Alkali Inspector, these cylinders were placed in the direction of the prevailing winds and at right angles to that direction, and at distances of approximately 8 to 10 times the chimney-height from the power-station.

Table V gives the results of these tests from the 1st April, 1936, to the

[1] Department of Scientific and Industrial Research, "The Investigation of Atmospheric Pollution. Report on Observations in the year ended 31st March, 1932; 18th Report." H.M. Stationery Office, London, 1932.

31st December, 1937. It will be seen from these results that the operation of the Fulham power-station, which was put into commercial service on the 1st November, 1936, has had no apparent effect on the atmospheric pollution. An analysis of the figures is interesting, however, in that it shows that sulphur-activity in London varies roughly with the seasons, being high in the winter months and low in the summer months. As it may be assumed that industrial activity does not vary to any marked

TABLE V.—SUMMARY OF RESULTS OF ATMOSPHERIC-POLLUTION TESTS IN FULHAM DISTRICT. 1ST APRIL, 1936, TO 31ST DECEMBER, 1937. LEAD-PEROXIDE CYLINDER METHOD.

(Pollution expressed as milligrammes of SO_3 per 100 square centimetres per day.)

Month.	1. Blake House.	2. Old Battersea House.	3. Chelsea Basin.	4. Fulham Library.	5. Mead Ambulance Stn.
1936.					
April . . .	4·14	3·47	4·82	7·13	3·80
May . . .	2·92	2·12	2·12	1·95	2·25
June . . .	2·64	1·76	2·43	1·43	1·72
July . . .	2·60	1·76	2·43	0·96	1·72
August . .	3·80	2·50	3·40	1·80	2·40
September .	4·10	3·13	3·17	1·53	1·93
October . .	6·50	3·10	4·60	2·40	2·70
November .	8·60	4·40	5·90	4·00	4·30
December .	6·50	3·60	5·10	3·20	3·20
1937.					
January . .	5·42	4·01	4·30	3·77	3·77
February .	6·24	3·93	5·25	2·66	2·96
March . .	5·25	3·36	4·20	3·85	2·97
April . . .	6·13	3·50	4·75	3·22	2·87
May . . .	2·14	2·15	3·09	2·20	3·85
June . . .	2·64	1·96	2·20	0·85	1·08
July . . .	2·96	1·49	2·36	0·64	1·05
August . .	2·25	1·52	2·20	1·05	1·24
September .	3·93	1·75	3·20	1·23	1·52
October . .	7·45	3·47	3·69	3·78	3·60
November .	8·77	5·22	6·84	5·97	4·53
December .	5·64	4·77	6·90	5·00	4·80

extent with the seasons, it would appear that the large increase in sulphur-activity in the winter is mainly due to household or office heating, either directly or indirectly. A few individual results invite comment. For instance, the extremely high figure of 8·6 milligrammes of SO_3 per 100 square centimetres per day, recorded for November, 1936, on the roof of Blake House, is explained by the prevalence of a north-east wind throughout that month. As the cylinder was surrounded by domestic chimneys, it was apparent that due to heavy firing necessitated by the cold weather a considerable amount of smoke from domestic fires had attacked the lead peroxide.

In examining these results it is well to bear in mind that during the

period from the 1st November, 1936, to the 31st December, 1937, 306,845 tons of coal were burnt at the Fulham power-station, representing the burning of 2,766 tons of sulphur.

Steam-System.

The aim in the design of the steam pipework system has been to produce a scheme of connexions whereby sufficient flexibility is obtained; due regard has been paid to allowable stresses, also to such factors as the elimination of unnecessary joints and the production of maximum lengths of straight piping incorporated with bends.

Turbine-Room Plant.

Turbines.

The main generating plant in the station consists of three turbo-alternator sets, each of 60,000 kilowatts maximum continuous rating, running at 1,500 revolutions per minute. Each of the turbines is of the two-cylinder impulse type, and a section of one of the units is shown in Fig. 13, Plate 1. The designed initial steam-conditions are 600 lb. per square inch and 800° F.

The high-pressure cylinders each comprise a velocity-compounded stage followed by twenty-one single impulse-stages, and the low-pressure cylinders incorporate thirteen impulse-stages followed by a duplex multi-exhaust.

The high-pressure cylinder is of steel throughout, the top and bottom halves each being formed of two steel castings, one comprising the main bed of the cylinder and the other end containing branches for conveying steam through coupling pipes to the low-pressure cylinder. These cylinder-interconnexions are arranged just above floor-level and are provided with expansion-pieces of corrugated section.

The diaphragms of the high-pressure cylinder are all of the built-up type consisting of molybdenum-steel plate centres to which are fitted and riveted independently-machined nozzles of molybdenum steel; in accordance with the latest practice for large turbines they are provided with a special three-point method of support to constrain them to expand concentrically with the shaft, and at the same time to maintain the diaphragm-joint in a steam-tight condition.

The inner peripheries of the diaphragms surrounding the shaft are provided with packing rings of the comb type, similar in formation to the gland at the exhaust end of the high-pressure cylinder which is described below.

The moving blades of the high-pressure cylinder are of rolled-section stainless steel with separate packers, except those of the velocity-com-

pounded stage which are machined solid with their packers from stainless steel. All blades and packers have T-shaped roots.

The gland at the inlet end of the high-pressure cylinder is of the radial-clearance comb type and is formed of steel segment-rings, each of which with a corresponding portion of the rotor provides a number of throttling points. Each ring is backed by a series of flat springs, while further flat springs supported the ring-housings containing three or four rings. In this manner both individual rings and the housings themselves are capable of lateral displacement, in the event of accidental contact, while maintaining the original formation of the gland. This high-pressure gland comprises two main sections and provides seventy-two points of throttling.

The gland at the exhaust end of the high-pressure cylinder is designed on the same principle as the high-pressure gland, but a somewhat different form is adopted for the gland-ring throttling strips to allow for expansion of the rotor relative to the casing.

The diaphragms of the low-pressure cylinder are of cast iron with cast-in steel blades, except for the diaphragm of the final stage which is of welded steel-plate construction. The first seven wheels have blades of rolled-section stainless steel with T-roots and separate packers, the remaining blades being of the straddle type machined solid with their distance-pieces from alloy steel and riveted to the disks.

The gland at the inlet end of the low-pressure cylinder is of the same type as that at the inlet end of the high-pressure cylinder but has fewer segments. The exhaust end of the cylinder is fitted with a water-sealed gland supplemented by simple labyrinth rings.

The thrust-blocks of both high- and low-pressure cylinders are of the latest Michell type and are located at the inlet ends of the respective cylinders.

A Bibby-type coupling connects the high- and low-pressure rotors, while the low-pressure shaft is coupled to the alternator shaft by means of a semi-flexible coupling.

The main governor is of the horizontal type and is driven, together with the main oil-pump, by means of helical gears. The governor, with its axis parallel to the shaft, is arranged on one side of the pedestal, while the oil-pump is carried on the other side. The governor is provided with ball bearings at all pivoted joints.

With very large plant, where duplicate groups of main steam-admission valves are employed, one on each side of the high-pressure cylinder, the usual hydraulic method of controlling the steam-valve power-pistons direct from the governor relay-valve tends in some degree to impair the sensitivity of governing. On the units in question this tendency is eliminated by introducing mechanical links between the governor and the two steam-chests.

Briefly, the governing system consists of a governor with its operating

arm actuating duplicate relay-valves, which control two adjacent power-pistons. These power-pistons are coupled through mechanical linkages to relay-valves, one on each steam-chest, controlling two horizontal power-cylinders having extended shafts provided with cams, one for each steam-valve. Relay-valves mounted above the steam-valves and actuated by the cams control oil-admission to the power-cylinders operating the steam-admission valves. Compensation is provided at each relay-valve for adjustment of the setting.

The system outlined above has three main advantages. Firstly, the relay-valves that actuate the steam-valve power-cylinders are formed in the power-cylinders themselves, so ensuring rapid response to relay-valve movement. Secondly, the camshaft relay-valves are arranged immediately adjacent to the horizontal power-pistons which they operate. Thirdly, the lift applied to the steam-valve spindles is powerful, direct, and free from any bending moment that might cause the spindles to bind in the guides. The steam-valve power-pistons are coupled to the steam-valve spindles through a rigid bridge arrangement which obviates the use of oil glands under pressure.

For each 60,000-kilowatt unit two valve-groups, each comprising one emergency stop-valve and three steam-admission valves, are arranged one on each side of the high-pressure cylinder; the corresponding pairs of valves operate together. As already stated, each group is controlled by its own governor-relay pilot-valve, the two systems being entirely separate beyond the common governor operating arm. The first corresponding pair of governor-valves admits steam from the steam-chest to the first stage and operates for loads up to 36,000 kilowatts; the second pair admits steam after the first stage and deals with loads up to 48,000 kilowatts; while the third pair admits steam after the fifth stage and deals with loads up to 60,000 kilowatts. An important feature of the governor-valves is the provision of spring loading above the power-pistons operating the steam-valves, the closing action under a sudden reduction in load being quicker than where oil-pressure is used for closing.

Steam is admitted to the steam-chests through centre-pressure valves of a special type having a central by-pass valve, and also an atmospheric drain which opens after the valve is closed and so prevents any possibility of steam-leakage into the turbine causing corrosion. The operation of the valve is so arranged that the atmospheric drain is closed first, after which the by-pass opens, and finally the working valve opens. This arrangement provides a safeguard against omitting to open the atmospheric drain when the set is shut down.

The safety governor is of the ring type, in duplicate; when overspeed occurs it trips a valve which releases the oil-pressure in the operating power-cylinders of the emergency stop-valve and of the steam-admission valves, causing them instantly to close by spring action.

House-Service Set.

The house-service generating set, which is located at the southern end of the turbine-room, is of the Ljungström double-rotation radial-flow reaction type, the two sections of the machine running in opposite directions at a speed of 3,000 revolutions per minute. The set is of 10,000 kilowatts maximum continuous rating at a power-factor of 0·8 lagging, and the nominal terminal pressure between phases is 6,600 volts at 50 cycles per second.

The turbine comprises forty radial-flow stages and two axial-flow stages, the latter being provided with fixed guide-blades and arranged to form a double axial-flow exhaust in the same casing as the radial-flow stages. The whole of the high-pressure turbine-blading is of stainless steel, but the axial-flow blades are of chrome-nickel steel. At the time of installation the machine was unique in that it was the first example of the Ljungström principle applied to the same steam-conditions as the main plant, namely 600 lb. per square inch and 800° F.

Main Condensing Plant.

Each condenser is of the regenerative type, and each shell contains 54,000 square feet of cooling surface. The condensers are arranged for half-cleaning, each portion of the condenser being served by a separate circulating pump. Experience has shown that the divided type of condenser is essential for stations situated in similar localities to the one under review. The Fulham station, in particular, is subjected to a very heavy influx of leaves and other debris during a period of approximately 3 months following the autumn, and the arrangement provided has enabled continuity of supply to be maintained at half full load of each machine during cleaning operations.

The main technical details of each condensing plant are shown in Table VI (p. 40).

Feed-Heating System.

The feed-heating system adopted is very complete, differing from that of many other large installations in Great Britain in that it embodies, for each main unit, de-aerating plant constituting a feed-heating stage; the complete system comprises one low-pressure heater, one gland heater, one de-aerating heater, and three high-pressure heaters, supplemented by the ejector-coolers. Double-effect inter-stage evaporators are also installed and form an integral part of the feed-system. The diagrammatic layout of the feed-system is shown in *Fig. 14* (p. 41) which refers to one turbo-unit.

It is appreciated that corrosion of boilers and other parts handling hot water is due mainly to the presence in the water of oxygen dissolved from the atmosphere. The amount of oxygen that can be retained in solution

is proportional to the partial gas-pressure and also depends inversely on the temperature of the water. In the type of de-aerator installed the conditions favourable to gas-liberation are obtained by raising the feed-water to the temperature of the steam atmosphere through which it falls; at the same time a quantity of steam, greatly in excess of that required for merely heating the water, is passed through the de-aerator shell. As the boiling-point of the water corresponding to the pressure is reached, the dissolved gases are driven out of solution into the current of steam passing over the surface of the water and ultimately pass to the condenser steam-space, from which they are rejected by means of the air-ejectors.

The de-aerating heaters employed are of the contact type. The complete de-aerator for each unit consists of a de-aerator chamber proper,

TABLE VI.

Rating	Maintaining continuously 29 inches vacuum (barometer at 30 inches) when dealing with 405,000 lb. of steam per hour containing 915 B.Th.U. per lb. plus 34,200 lb. per hour condensed steam at a temperature of 164° F., when supplied with 2,496,000 gallons of cooling water per hour at 55° F.
Cooling surface	54,000 square feet.
Number of tubes	9,056.
Material of tubes	Admiralty mixture.
Length between tube-plates	22 feet $9\frac{7}{16}$ inches.
Thickness of tube-plates	$1\frac{1}{4}$ inch.
Velocity of water through tubes	5·5 feet per second.
Condenser friction	9·3 feet head.
Air-ejectors	Two: capacity 100 lb. dry air per hour each.
Extraction-pumps	Two: capacity 750 gallons per minute each, at 180 feet head.
Circulating-water pumps	Two: capacity 22,500 gallons per minute each, at 30 feet head.

a reservoir-tank mounted below and connected to the base of the de-aerator chamber, and a vapour-condenser. The de-aerated water falls to the storage-tank below, which serves as a reservoir on the suction side of the lift-pump that delivers the de-aerated feed to the first high-pressure heater. The surplus vapour from the de-aerator chamber passes with the incondensible gases liberated to the vent-condenser, through the tubes of which the water-supply to the de-aerator passes; thus it serves as a water-preheater and air-concentrator. The vapour condensed in this process is drained back to the base of the de-aerator, while the incondensible gases are passed to the main condenser.

The surge-system comprises four main tanks, each of approximately 300,000 lb. capacity. These tanks are joined together by a common bus-main.

The lift-pumps which deal with the water extracted from the de-aerator hotwell are of the constant-speed motor-driven type, and are capable of

Fig. 14.

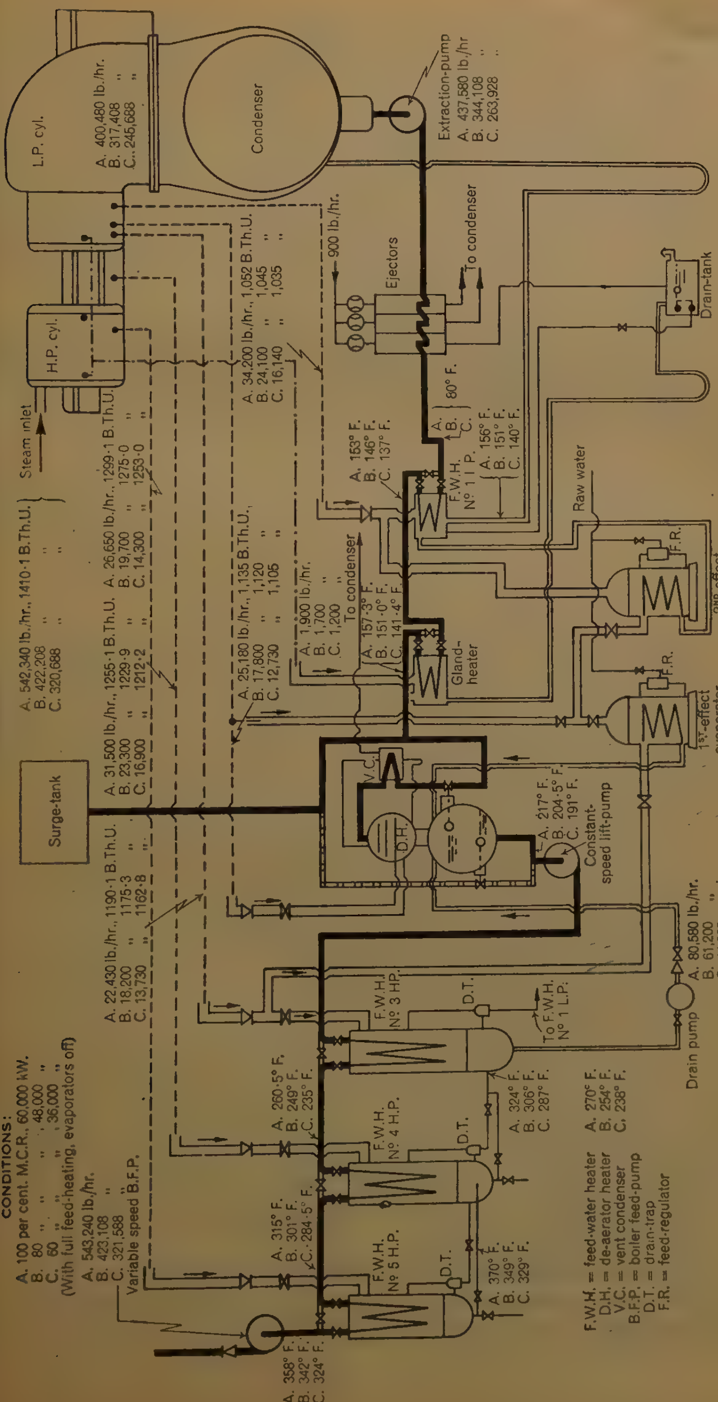


DIAGRAM OF FEED-SYSTEM AND HEAT-FLOWS FOR ONE TURBO-UNIT.

delivering 630,000 lb. of water per hour at a temperature of 220° F. against a pressure of 250 lb. per square inch through the three stages of high-pressure feed-heating to the suction bus-pipe of the final boiler feed-pumps, which are motor-driven and are equipped with hydraulic couplings for automatic or manual speed-control. These latter pumps deliver 630,000 lb. of water per hour at the full feed-temperature of 358° F. against a total pressure of 800 lb. per square inch absolute, the pressure on the suction side being 238 lb. per square inch absolute. Two turbine-driven feed-pumps of the horizontal direct-coupled type are connected to the feed-circuit for emergency purposes.

The make-up to the system is obtained by the evaporation of river-water in two-stage evaporators supplied with steam from the tapping supplying the first high-pressure heater, the capacity of the evaporating plant being 37,000 lb. per hour per main set at maximum continuous rating.

As will be seen from *Fig. 14*, p. 41, the complete feed-heating system provides for a final feed-temperature of 358° F. at maximum continuous rating.

Circulating-Water System.

Site-limitations determined the relationship of the circulating-water intake-works to the outfall-works, and whilst it was the designer's aim to take advantage of the maximum available natural cooling by spacing these two points as far apart as possible, the question of reasonable capital expenditure involved in the constructional works had to be borne in mind. Due consideration of the above points resulted in the intake being located some 420 feet upstream from the main discharge-works.

The station-design adopted entailed the placing of the main condensers at such a level as to call for the minimum amount of pumping compatible with reasonable costs of excavations and foundations. This enabled a system to be evolved whereby the water from the river was allowed to gravitate to the circulating-water pumps, which are drowned at all states of the tide.

The circulating water required for the completed station having a generating capacity of 310,000 kilowatts, taking into account raw-water requirements for evaporators, sealing water for pumps, and such auxiliary services, will amount to approximately 14·5 million gallons per hour. The quantity required solely for condensing purposes for each 60,000-kilowatt unit in order to maintain a 29-inch vacuum with barometer at 30 inches, and assuming an average river-water temperature of 55° F., is approximately 2,500,000 gallons per hour.

The aim in designing the intake-works was to enable the quantity of water mentioned to be extracted from the river without creating dangerous currents or eddies. The river-bed between the deep-water channel and

the intake had to be considerably deepened, forming a tapered intake-channel. Concrete training-walls form the inshore 40 feet of this channel.

The intake-chamber consists of a mass-concrete pit provided with six openings at the river front, each opening of 16·5 by 8·76 feet providing a total inlet-area of 864 square feet when completely submerged, and being protected by a screen of mild-steel bars at 4-inch centres. Each of these openings is connected to one rotating-band screen; these screens are grouped in two sets of three, and complete isolation of either set can be brought about by penstocks. Each set of three screens is connected to an inlet-tunnel 9 feet 6 inches in diameter, the dimensions of the screens and the tunnel being sufficient to supply the present station. Isolation of the tunnels can be effected both at the intake-end and at the station central distribution-chamber referred to later.

The two tunnels proceed in parallel in a westerly direction towards Townmead road, and within the confines of the site turn at right angles in a northerly direction, terminating in a central distribution-chamber on the west side of the circulating-water pump bay. This chamber is constructed in mass concrete, being divided into two main compartments, from which are taken the individual supplies via 6-foot 6-inch diameter tunnels to vertical shafts from which the circulating-water pumps connected to the respective condensing plants draw their supply.

The supplies of condensing water for each main unit are handled by two axial-flow pumps situated in the basement of the circulating-water pump bay, drawing their water from the surge-shafts referred to. The condenser of the auxiliary or house machine is also supplied by two similar pumps, one of which takes its water from the surge-shaft supplying No. 1 main machine and the other from the surge-shaft supplying No. 2 machine. By this means a supply of cooling water for the auxiliary machine can be maintained during overhaul or inspection of an individual surge-shaft and tunnel.

The discharge-water from each individual condenser is received by a separate pipe 5 feet in diameter buried in the basement-raft of the turbine-room. The pipes proceed from the condensers in a northerly direction, entering a sunken mass-concrete chamber at the north end of the site; each discharge-pipe can be isolated from the main chamber by means of a penstock, thus enabling inspection to be made when required.

A single 10-foot 6-inch diameter tunnel conveys all discharge-water from this chamber to the outfall, terminating in a chamber which is provided with three separate penstock-controlled exits to the river. Each of these three exit-channels can be kept clear by occasionally shutting off the others, thus increasing the velocity of the discharge.

Advantage is taken of siphonic effect, and the speed of the circulating-water pumps can be varied, which provides for economy at times of low river-water temperature.

Main Alternators.

A section through a main alternator-set, showing the alternator and the main and pilot exciters, is given in Fig. 15, Plate 1. Each alternator is rated at 75,000 kilovolt-amperes, maximum continuous rating, at 0·8 power-factor lagging, and is wound for a voltage of 11,000, at 50 cycles per second. The rotor consists of a solid 53-inch diameter forging, which is bored from end to end for inspection purposes. The cone retaining-rings are of high-tensile non-magnetic steel in order to reduce the leakage-field losses. The rotor weighs 58 tons and the stator 91 tons.

The main exciter is designed to have special quick-response features, the field-system being completely laminated and the ceiling-voltage being over 100 per cent. more than the normal operating voltage. It is excited from a pilot exciter which is overhung from the main-exciter shaft.

The alternator is cooled on the closed-circuit system, air being circulated by two fans mounted at the ends of the rotor, supplemented by two external motor-driven fans. The motor-driven fans are of the high-speed propeller type, and are driven by 90-h.p. motors and mounted horizontally in the air-chamber inside the foundation-block.

Steam Tests.

Official steam-consumption tests have been carried out on No. 2 machine in the manner usual in feed-heating installations while the machine was operating under commercial load, and with conditions maintained steady and as near as possible to those under which consumption was guaranteed. The condensate was measured by calibrated tanks coupled in the feed-circuit after the gland-heater. The drains from the three high-pressure heaters were diverted for the purpose of test and mixed with the condensate before the measuring tank, the drains from the low-pressure heaters and ejector-heaters being led back to the condenser. In the case of the de-aerator heater, as the steam bled from the turbine was mixed with the condensate after the measuring tanks, it was necessary to estimate the steam used by the temperature-rise in this heater, and this estimated quantity was added to the condensate actually measured in the tanks.

The electrical output was measured by two integrating polyphase watt-hour meters previously calibrated with their respective current-transformers.

The steam-temperature was taken as the average of two readings of Whipple thermometer indicators previously checked against a calibrated mercury-in-glass thermometer. All other temperature-measurements were made by mercury-in-glass thermometers previously calibrated at the National Physical Laboratory.

Pressure-gauges were carefully calibrated for the tests by a dead-weight tester, and the vacuum at the turbine-exhaust was measured as the average of four mercury columns corrected for temperature and barometric pressure.

Pressures and temperatures were also read (in duplicate wherever possible) at various stages in the machine for the determination of the condition-line.

Temperature-readings were also taken in the bled-steam pipes, in the condensate entering and leaving each heater, and in the drain of each heater. As such additional readings were taken with the same care as those essential merely to check contract obligations, they afforded repeated checks on themselves and on the contract readings.

All corrections for variations from standard test-conditions were agreed prior to the tests, the total correction being of the order of 1 per cent., with the exception of the test at 60 per cent. load, in which case the correction was 2·6 per cent.

A summary of the results of these tests is given in Table VII.

TABLE VII.

	No. 1 governor-valve.	Nos. 1 and 2 governor-valves.	Nos. 1, 2 and 3 governor-valves.
Actual load: kilowatts . .	29,333	52,452	60,228
Steam-pressure at stop-valve: lb. per square inch gauge .	594·4	590·6	588·2
Steam-temperature at stop-valve: ° F.	797·8	808·2	805·7
Mean vacuum at exhaust, corrected to 30 inches and 32° F.: inches	28·923	28·549	28·313
Final feed-temperature: ° F. .	306·33	351·30	365·5
Corrected consumption: lb. of steam per kilowatt-hour .	9·016	8·888	9·228
Corrected consumption: B.Th.U. per kilowatt-hour	10,128·6	9,748·3	9,974·4

These tests showed that the manufacturer's obligations in regard to steam-consumption were met.

VOLTAGE OF GENERATION.

The decision to generate at 11,000 volts and step up to 66,000 volts by means of transformers directly coupled to the generators was taken in view of the fact that 66,000-volt generators are not yet a practical proposition. The highest generating voltage in use up to the present time is 33,000 volts. Generators even of that voltage are still perhaps a little experimental, but there is some justification for using them where 33,000 volts is the final voltage required. Where, however, a still higher voltage is required and transformers have to be used in any case, a lower generating voltage is to be preferred. In the selection of this lower voltage the

designers are usually given some latitude to enable them to produce the most economical and efficient design and the voltage-ratio of the transformer is selected accordingly. In the present instance, 11,000 volts was found to be most suitable, and at this voltage a very robust and well-tried type of machine can be produced.

Various manufacturers are still experimenting with 66,000-volt insulation for generator-windings, but they have not yet reached the stage where they would definitely offer a 66,000-volt machine. There are, however, no technical reasons to suppose that any insuperable difficulties will be met in this direction. On the other hand, there is not much incentive to press for 66,000-volt generation, as at that voltage the cost of the generator would be of the same order as that of the combined 11,000-volt generator and step-up transformer, and also the efficiencies would be much the same. There would be no difficulty in obtaining a suitable value of reactance, as the reactance of a 66,000-volt machine would be approximately the same as that of a 11,000-volt machine and transformer. The only possible advantage, in the present state of design, might be a possible saving of the space occupied by the step-up transformer.

Main Transformers.

There are three main transformers, each rated at 75,000 kilovolt-amperes, stepping-up the generated voltage from 11,000 to 66,000 volts, with delta-connected low-voltage and star-connected high-voltage windings. They are of the oil-immersed type, provided with forced oil-circulation and water-cooling, and are of more or less standard design.

In view of the close proximity of residential property, special attention was paid to minimizing the noise emitted from the transformers. The steps taken included the designing of the transformers with a reduced flux-density in the core and a substantial and well-clamped core, and the provision of rubber pads between the tanks and the supporting floor so as to minimize the communication of vibration to foundations. Direct emission of noise is prevented by housing each transformer in a massive brick chamber, the entrance being finally bricked up so that no openings are left.

Auxiliary Supplies.

The power required for auxiliary or house-service supplies is approximately 8,000 kilowatts with the present installation working at economic ratings.

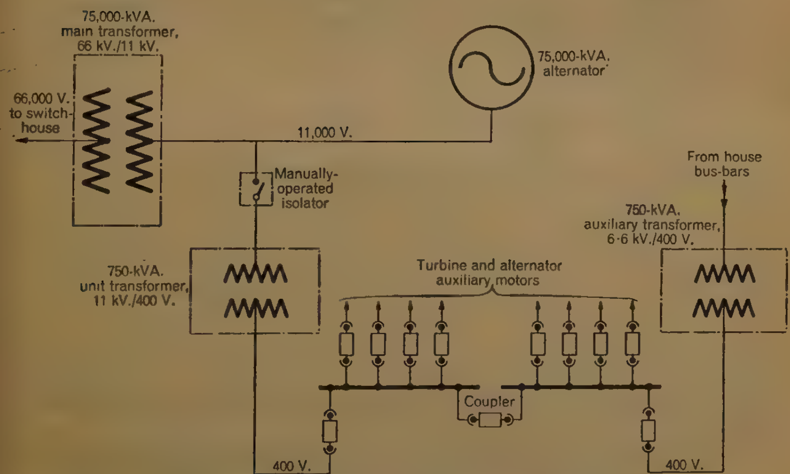
There are three main sources of supply :—

(a) One Ljungström 10,000-kilowatt 6,600-volt turbo-alternator, already described (p. 39).

(*b*) Two 12,500-kilovolt-ampere house transformers, one of which is provided with oil-pumps, oil-coolers, etc., for use on ordinary circulating-water supplies, whilst the other is of the outdoor self-cooled type. These transformers are wound for 66,000 volts primary and 6,600 volts secondary, the primaries being energized from the station 66-kilovolt busbars.

(*c*) One 750-kilovolt-ampere self-cooled transformer per main turbo-alternator. These transformers are teed straight on to the 11,000-volt terminals at the alternators. The secondary side supplies the appropriate 400-volt busbars through circuit-breakers (*Fig. 16*).

Fig. 16.



MAIN ALTERNATOR AND TRANSFORMER CIRCUITS.

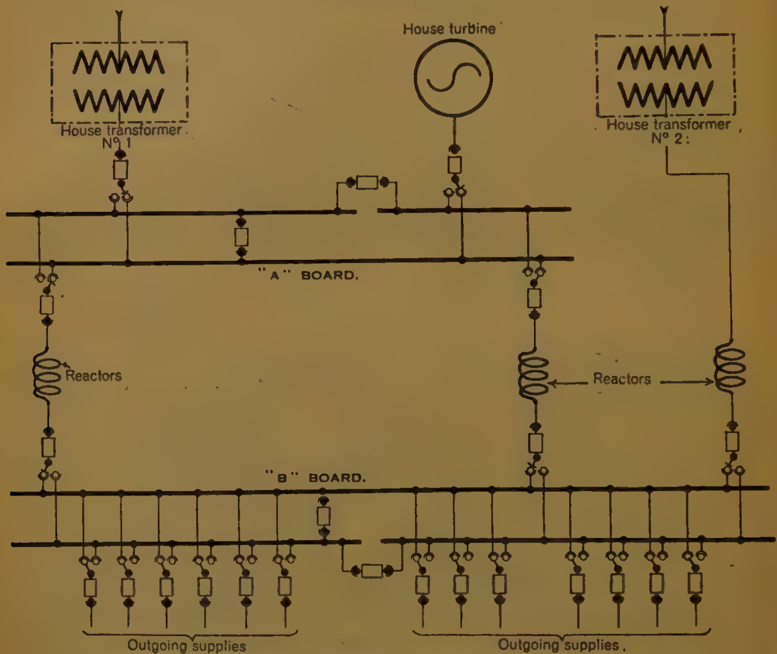
The output from both (*a*) and (*b*) is taken at 6,600 volts to the station auxiliary busbars (situated on the + 90 O.D. level of the feed-pump bay), as shown in *Fig. 17* (p. 48). These incoming supplies are taken to what is known as the " A " board via oil circuit-breakers of the metal-clad double-busbar draw-out type, rated at 250,000 kilovolt-amperes. This " A " board is connected to the " B " (or Distribution) board by means of cast-in-stone air-cored reactors.

The " B " board consists of thirty-one metal-clad double-busbar draw-out type oil circuit-breakers, each having a rupturing capacity of 150,000 kilovolt-amperes, the lay-out of the board comprising three incoming reactor feeds, one section and one coupling switch, and twenty-six feeders.

The whole of the switchgear of the " A " board and " B " board is arranged for solenoid operation.

A control-room for the remote operation of this switchgear is provided at the north end of the feed-pump bay. The incoming feeders are controlled from a desk of the cubicle pattern, containing the usual synchronizing control and indication-apparatus. Since the second house-transformer is a part of the final extension to the station, and, in consequence, will eventually be connected to a future duplicate "A" board, this source of auxiliary power is temporarily connected direct to the "B" board via a reactor.

Fig. 17.



STATION AUXILIARY BUSBAR CIRCUITS.

All generator, transformer, and reactor oil circuit-breakers on both "A" and "B" boards are fitted with on-load busbar-selection equipment. Other circuits are arranged for off-load selection.

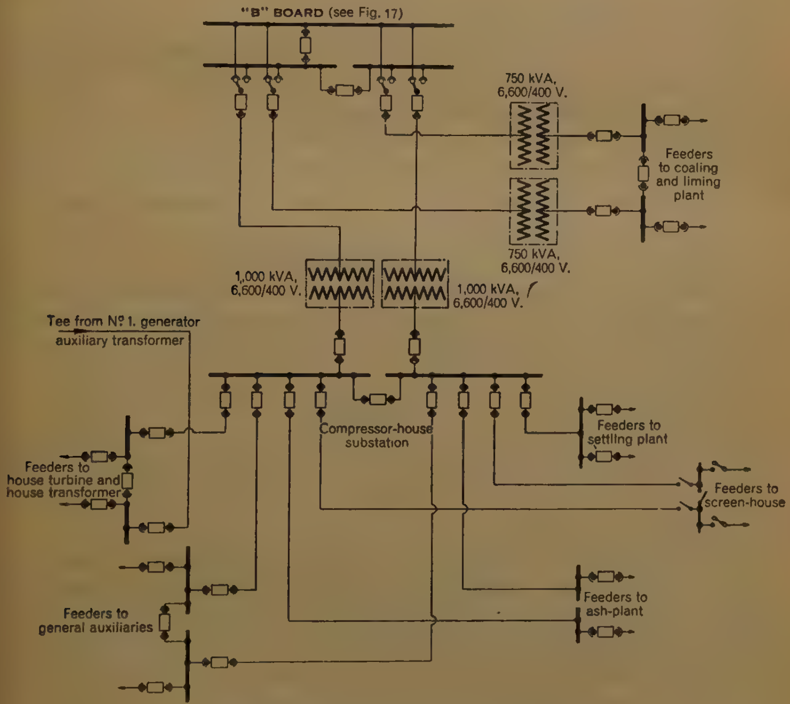
All feed-pumps are direct-switched at 6,600 volts, there being no switch or starter in the circuit other than the appropriate circuit-breaker at the "B" board. Switching in these cases is remote-controlled from the panels adjacent to each of the feed-pumps, and it is of interest to note that the initial starting kick on the high-pressure pump-motors is of the order of 7,000 kilovolt-amperes.

In regard to auxiliary supplies to the boiler-house, each boiler is treated as a unit and is provided with one 950-kilovolt-ampere air-blast trans-

former. The eight groups of transformers and associated switchgear for the eight boilers now installed are housed on the + 116 O.D. level above the coal-bunkers and in two lines parallel to the centre-line of the present boiler-house, the switch-aisle being partitioned off from the rest of the boiler-house.

The turbo-alternator main auxiliaries, as indicated in *Fig. 16* (p. 47) are supplied from either the 750-kilovolt-ampere unit transformer or a 750-kilovolt-ampere turbine auxiliary transformer. Each auxiliary transformer

Fig. 18.



ARRANGEMENT OF AUXILIARY SUPPLIES.

is supplied direct from the "B" board, and either this transformer or the unit transformer may be used for all auxiliaries for the particular set to which they are connected. In service it is preferred to supply half the auxiliaries from each source, with the coupler-switch between open.

The supplies for the coaling plant, liming plant, and other auxiliaries are arranged as shown in *Fig. 18*; this figure does not include the turbo-generator auxiliaries, which are indicated in *Fig. 16*, or the feed-pump and boiler auxiliaries, which are treated as units. The compressor-house switchboard is equipped with a neutral busbar for use on the station lighting and heating circuits.

In general, where a sub-switchboard is fitted with two incomers and a coupler, interlocks are provided to prevent more than two or three oil circuit-breakers being closed together. This precaution prevents the paralleling of the two halves of any board, and is necessary because it may be required, in practice, to operate the main "B" board in two separate sections.

In normal operation, therefore, the sub-boards are operated with both incomers alive and closed, the coupler-switch remaining in the open position.

Protection of Auxiliary Network.

The protection of the auxiliary network consists primarily of a time-graded overload and earth-leakage scheme covering every circuit of the network from the main station auxiliary board, on to which the house transformer and house generating-set feed, down to the smaller distribution-boards at the far end of the network. In addition to this, certain circuits are equipped with discriminative protective gear, more especially duplicate supply-circuits connected in parallel.

All the relays in the graded scheme are of the definite-minimum inverse-time type. Generally speaking the definite-minimum time-settings are adjusted to give adequate discrimination between the several stages of the distribution-network, and the overload-settings are adjusted in conjunction with the time-settings so as not to operate during the starting period of the direct-started motors. The starting switches of certain motors are, however, arranged so that the overload-relay is cut out of operation during the starting period. Generally speaking, therefore, the protection on the motors is in the nature of fault-protection rather than pure overload-protection.

The discriminative protection consists of either Merz-Price circulating-current or restricted earth-leakage protection. The house generating-set has Merz-Price protection which trips the main switch, the field switch and the neutral-earthing switch. The house transformers have restricted earth-leakage protection on the 6·6-kilovolt side with intertripping to the 66-kilovolt side. The two reactor-circuits, which normally run in parallel, are both equipped with Merz-Price protection. There is also restricted earth-leakage protection on the 400-volt side of the unit and auxiliary transformers supplying the generator-unit auxiliary boards, and similarly on the pairs of parallel transformers supplying the compressor-house and coaling-plant boards.

All auxiliary transformers are fitted with Buchholz relays with preliminary alarms and final trip contacts. These relays respond to the production of gases in a transformer resulting from a fault. In addition, each auxiliary transformer is fitted with oil- and winding-temperature indicators and alarms.

For the protection of the smaller motor-circuits high-rupturing-duty

fuses of the cartridge type are used. These, again, are set to blow at a margin above the starting current of the motor, and they are, therefore, more in the nature of fault-protection than pure overload-protection. It should be made clear that the protection in the motor-circuits, as actually in the case of all other circuits, is not so much to protect the motor or the individual circuit itself, but rather to protect the rest of the system from being dislocated by a fault on a motor. Most of the motors in a power-station have loads of such a nature that they cannot be overloaded in the usual manner; moreover, the functions of many of the auxiliaries are so important as to make it undesirable to bring them out for anything short of a fault which, if not interrupted, would dislocate the rest of the auxiliary system.

Main Switchgear.

The main switching is performed at 66 kilovolts, the output-voltage of the main transformers. A cable-tunnel connects the extra-high-tension side of the transformers with the switch-houses, whose position is indicated in *Fig. 6* (p. 18). The complete design of the station incorporates five separate switch-houses and one transfer-reactor switch-house. The main reason for this physical separation is fire-protection, as discussed later in the Paper (p. 60). Each switch-house contains switchgear for one turbo-alternator, four feeders, and one tie-reactor. The switchgear is of the metal-clad type, employing duplicate circuit-breakers for each circuit, one capable of connecting the circuit to the main busbar and the other to a reserve or transfer busbar. At present there are thirty-eight remote-electrically-operated breakers.

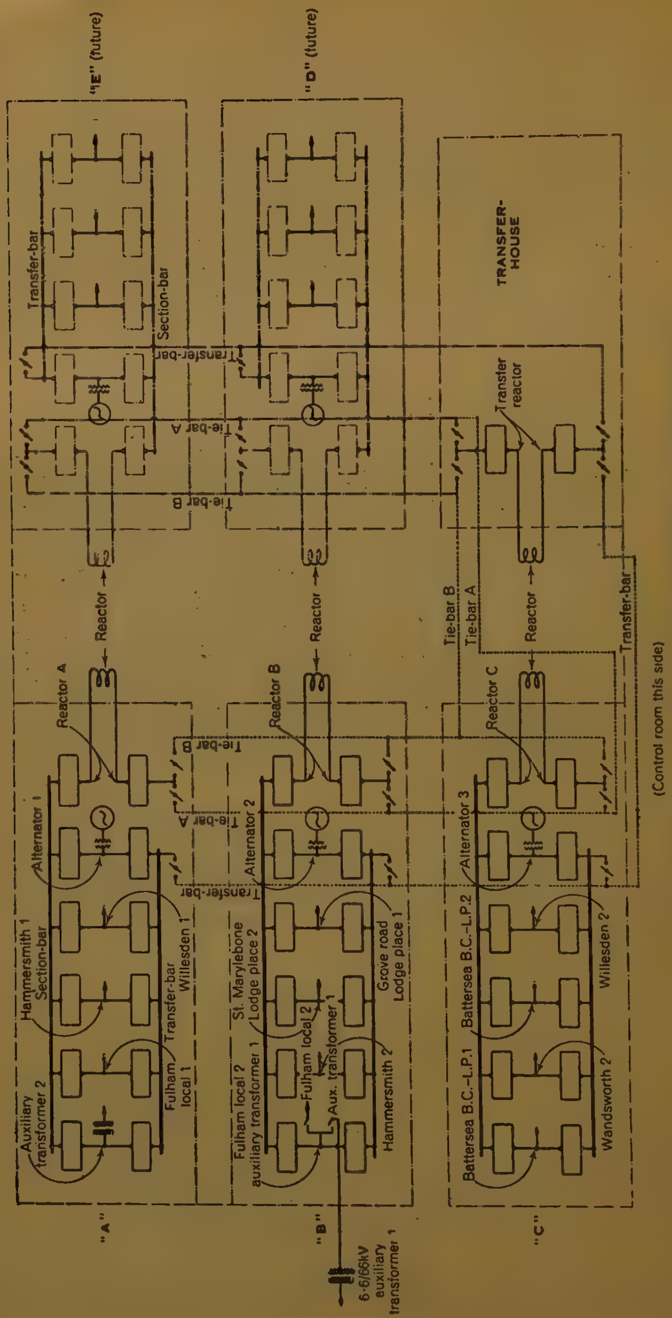
The circuit-breakers are of the two-break type, each break taking place within a cross-jet pot assembly, as shown in detail in Fig. 19, Plate 1. Phase-isolation is adopted, each phase being contained in a separate tank and all busbars, connexions and cables being of the single-phase type. The weight of the breaker, complete with oil, is 19 tons; other data are given in Table VIII.

Table VIII.

Length of stroke	18 inches.
Clear gap at each break	15·5 ,,
Rupturing-capacity	1·5 million kilovolt-amperes.
Speed at which auxiliary contacts open, with maximum fault-current	12 feet per second, each break.
Time required from closing of trip circuit to completion of stroke, with maximum fault current . .	0·26 second.

The main connexions are illustrated in *Fig. 20* (p. 52) from which it will be seen that each switch-house contains a section of the main busbar,

Fig. 20.



DIAGRAMMATIC ARRANGEMENT OF MAIN ELECTRICAL CONNEXIONS.

known as the "section" bar, and a section of the reserve bar, known as the "transfer" bar. Each section-bar is coupled to the other section-bars by duplicate tie-bars through tie-reactors, the latter limiting the amount of fault-current that can be fed into any section and so ensuring that the breakers are not called upon to exceed their rupturing capacity.

In addition, the "transfer" bars in the several switch-houses are capable of being coupled directly to a further tie-bar, which can in turn be connected to the main tie-bars through a "transfer-reactor," thus making an arrangement which allows for a very large degree of flexibility. It will be seen that a circuit may be connected to either busbar by one of the duplicate circuit-breakers, thus enabling maintenance-work to be carried out on the other circuit-breaker without shutting down the particular circuit. The duplicate circuit-breakers are disposed on either side of the switch-house, and the switch-house proper is divided into three levels, the operating platform being at + 36 O.D., the circuit-breaker floor at + 30 O.D., and the busbar floor at + 20 O.D. The tie- and transfer-bars are at + 8 O.D., the reactors are housed outside the switchgear building, and a bay is provided for testing circuit-breakers and auxiliaries.

The cable-basement is at – 3 O.D. All cables are of the oil-filled type, and oil-conservators to maintain the required oil-pressure are provided.

The busbars and other conductors are insulated by bakelized paper bushings of the condenser type, protected by a final layer of wire, which forms an effective earthed metal casing. The joints between the various lengths of busbars are made at the points where the connexions to the circuit-breakers or reactors are taken off, and are arranged within substantial connecting-boxes of non-magnetic metal. These boxes are oil-filled and there is no oil-interconnexion between them. The clearances in the boxes are designed to withstand the full working pressure continuously without oil.

The CO_2 equipment and other fire-protective measures are described later (p. 61).

In each testing bay there are pipe-connexions to tanks for clean and dirty oil; when it is necessary to change the oil in a switch-tank, the switch is taken by the crane (which is also used for isolating operation) to the testing bay, and the tank is drained by the dirty-oil pipe, inspected and cleaned, and refilled by the clean-oil pipe. Filtering equipment is provided for the periodical cleaning of dirty oil.

The maintenance of a constant temperature in the switch-houses is important to prevent "breathing" and moisture-condensation; for this purpose unit heaters are installed, consisting of heater coils, over which air is blown by fans. This system is adopted in view of the large area of the buildings and the many obstructions in them.

A communicating corridor runs across the end of each switch-house, and below this corridor is a cable-duct in which are run all the multicore

cables for the operation of the switches, so that the multicore cables are completely isolated from the power-cables.

In the control-room, all the feeder-control panels are arranged along one side with the alternator-control panels across the end, separated from the feeder-control panels by the sychronizing panels placed at an angle. Mimic diagrams are superimposed above the control-panels.

The equipment of the various panels follows the usual practice, but the frequency-control equipment is of interest. To enable electric clocks to be operated from the electricity-supply, it is more than ever necessary to control the generated frequency to within very fine limits in relation to standard time. A device is, therefore, provided in which an electric motor-driven clock supplied from the station frequency is compared with a standard clock, the pointers of both clocks appearing on the same dial. Actually, both pointers are driven by the same electric motor, but the pointer indicating standard time is connected to the spindle of the motor by a friction-clutch and its position is checked every 30 seconds by electrical impulses from a standard pendulum. If at any moment its position does not correspond to standard time, then the impulse checking device moves it round on the friction-clutch to the correct position. The speed of the alternators, and thus the frequency, is adjusted so that the two pointers remain as nearly as possible coincident. Although most of the principal stations in an area are equipped with such a device, it is impossible for a number of inter-connected stations to control their frequencies separately, and the duty of regulating the frequency of the whole group is therefore allotted to one of the stations.

A further point of interest is the provision of duplicate synchronizing-relays which ensure that any generator or other incoming circuit is in synchronism before being connected to the busbars by the closing of the circuit-breaker. One or other of these synchronizing relays must be plugged into the closing circuit of a circuit-breaker before the latter can be closed, and the closing circuit can only be made after the relay has checked that the busbar and incoming volts are in synchronism, and has accordingly closed its contacts. The relay consists of three elements, each containing two electro-magnets which actuate a rotating disk on the wattmeter principle. Each disk closes a pair of contacts when rotated in one direction and opens the contacts when rotated in the other direction. The rotation of each disk is lightly restrained by a spring. One electro-magnet of each element is connected to a voltage derived from the busbar voltage through a potential transformer and the other electro-magnet is connected to a voltage derived from the incoming circuit.

The incoming-voltage electro-magnet of two of the elements is connected through reactances and that of the other element through a non-inductive resistance. The disks rotate in one direction or the other, thus making or breaking their contacts, according to the phase-relationship between the busbar volts and the incoming volts. Due to the effect of (1) the

reactances, (2) the relative directions of the electro-magnet windings, and (3) the direction of the torque of the springs, all three elements will have their contacts closed simultaneously only when the voltages are in synchronism, thus allowing the circuit-breaker closing circuit to be completed under this condition and this condition only. Further, the disk of the resistance-fed element is damped magnetically to give it an appreciable time-lag, so as to ensure that the two voltages must be moving very slowly indeed in relation to each other to allow the circuit to be completed. Thus in the interval of time between the operation of the relay and the actual closing of the circuit-breaker the voltages cannot move very far from the position of true synchronism at which the relay operates.

Protective Gear.

The generator, step-up transformer and 66-kilovolt cables up to the circuit-breaker are covered by Merz-Price circulating-current protection. This is operated from star-connected current-transformers in the generator neutral connexions balanced against delta-connected current-transformers at the switchgear, the star—delta arrangement of the current transformers compensating for the star—delta connexion of the step-up transformer. In addition, the 66-kilovolt side of the step-up transformer and the 66-kilovolt cables are protected by restricted-earth-leakage protection, operated from the delta-connected Merz-Price current-transformers at the switchgear and a further current-transformer in the 66-kilovolt neutral-earthing circuit. Connexions are taken from these transformers to the windings of a summation-transformer which has a further winding connected to the restricted-earth-leakage relay. The connexions are so arranged that, should an earth develop within the protected zone (between the neutral point of the 66-kilovolt transformer-windings and the circuit-breaker), an unbalanced condition would be set up in the summation-transformer and a tripping current would be fed to the relay. Should, however, a fault occur outside the protected zone, the "residual" or out-of-balance current from the delta-connected current-transformers at the circuit-breaker would be balanced by the current from the neutral current-transformer and no tripping current would flow. An unrestricted-earth-leakage relay is also connected to the neutral current-transformer, and this would operate under all earth-fault conditions for a generator of which the 66-kilovolt neutral-earthing circuit happened to be closed at the time.

The Merz-Price protection and the restricted-earth-leakage protection, which only respond to faults within the protected zone, are set to operate in a minimum of time consistent with stability, but the unrestricted-earth-leakage protection, which would tend to operate whatever the position of the fault on the system, has to be time-graded to discriminate with similar

relays provided on other circuits. (This point is also referred to below, in connexion with busbar-protection.)

The generator-windings and the low-pressure windings of the step-up transformer form an entirely separate 11-kilovolt system, and the star-point of the generator-windings, which is the neutral point of this system, is nominally unearthed. It is merely connected to earth through a potential-transformer, the primary terminals of which are short-circuited by a fuse of high rupturing capacity. Should an earth fault occur on this separate 11-kilovolt system, all that would happen would be that the potential-transformer short-circuiting fuse would blow, the potential-transformer would become energized, and its secondary winding would operate an earth-leakage alarm. In the meantime the earth-current due to the fault would be restricted to the extremely small current which the impedance of the potential-transformer would allow to pass, and no harm could be done. In the very unlikely event of a second earth fault occurring, this would, of course, constitute a fault between phases and the Merz-Price protective gear would be brought into action. The operation of either the Merz-Price or the restricted-earth-leakage relay, indicating a fault internal to the generating plant, would trip the main circuit-breaker, the field circuit-breaker, the transformer-neutral circuit-breaker and the unit-transformer circuit-breaker. The unrestricted-earth-leakage relay, which would only be operated by an external fault, is arranged to trip only the main circuit-breaker.

The reactors are protected by restricted and unrestricted earth-leakage relays, the operation of either of which would trip both reactor circuit-breakers. Here again the restricted-earth-leakage relay, being discriminative, is given a minimum-time setting, and the unrestricted-earth-leakage relay is time-graded.

The feeder-protection is in the main of the split-pilot type which, as is known, is a special adaption of the Merz-Price principle. In addition, each feeder is equipped with an unrestricted-earth-leakage relay.

All the unrestricted-earth-leakage relays on the generator, reactor or feeder circuits are of the definite-minimum inverse-time type.

The foregoing describes the protection as it stands in the Fulham power-station to-day, but serious consideration is being given to the question of adding special busbar-protection. Owing to the scheme of complete phase-separation the busbar-system can only be subject to earth faults, and such faults are protected against to some extent by the existing unrestricted-earth-leakage relays with which every circuit connected to the busbars is equipped. In order to obtain discrimination, however, it is necessary for these relays to be time-graded in such a manner that the feeder-switches would tend to trip first, then the reactor-switches, and lastly the generator-switches. To achieve this it is necessary to give the generator-switches such a long time-setting that under the most favourable conditions they would take something like 2½ seconds to clear and under

less favourable conditions a very much longer time, which might in certain circumstances amount to minutes. Thus a fault of sufficient magnitude to cause very serious damage might be allowed to persist for a comparatively long time.

The special scheme of busbar-protection under consideration is discriminative, in that it would automatically select and clear the faulty busbar-section, leaving the remainder of the busbar-system intact. Under such an arrangement time-grading becomes unnecessary, and the relays can be set to operate in the minimum possible time consistent with stability. The scheme is made stable to all fault-conditions other than those under which it is required to operate by arranging that tripping of the circuit-breakers can only take place after two separate and independent conditions have been fulfilled, which sense the presence of a fault by different methods and are a check one against the other. Moreover, instead of all the circuit-breakers on a busbar-section being cleared by one relay responding to an earth fault on the section, each circuit is equipped with a separate relay so that should one of these relays be tripped inadvertently only one circuit would be affected. The two separate methods of relay-operation which check each other are as follows. In the one the total earth-fault current entering a busbar-section is balanced against the total earth-fault current leaving the busbar-section; should the fault be external to the bus-bar section the incoming and outgoing fault-currents balance and the relays would not operate, but if the fault should be within the busbar-section an out-of-balance would be obtained and the relays would operate. In the other method directional earth-fault relays are installed in each circuit connected to a busbar-section; the condition for clearing the busbar-section is that at least one circuit must be feeding fault into the section, but should even one circuit be feeding fault away from the section the tripping is definitely locked off all circuits connected to the section.

Owing to the added complication and the fear of dislocation due to inadvertent tripping, busbar-protection has not yet been generally adopted for major power-stations, but, in view of the serious damage that has been known to occur in the event of a busbar-fault not being cleared instantly, much more serious attention is being given to it at the present time.

Supervisory Indication to Bankside.

A supervisory equipment connects the main control-room with the main area control-room of the Central Electricity Board situated at Bankside. By means of this equipment the following indications of the conditions at the power-station are automatically given in the Bankside control-room :—

(1) Open or closed positions of 66-kilovolt circuit-breakers.
(2) Positions of 66–132-kilovolt transformer taps.

(3) Continuous reading of the outputs on the several groups of feeders and the total generated output of the station.

The principle of the supervisory equipment is such that the whole of the above indications could in theory be transmitted over a single pair of wires. Actually, on account of certain practical limitations two pairs of wires are used. For the transmission of the switchgear and transformer-tap signals a system based upon the automatic telephone system is used, whereby the particular point to be indicated is automatically selected and connected to one of the pairs of lines whenever a change takes place.

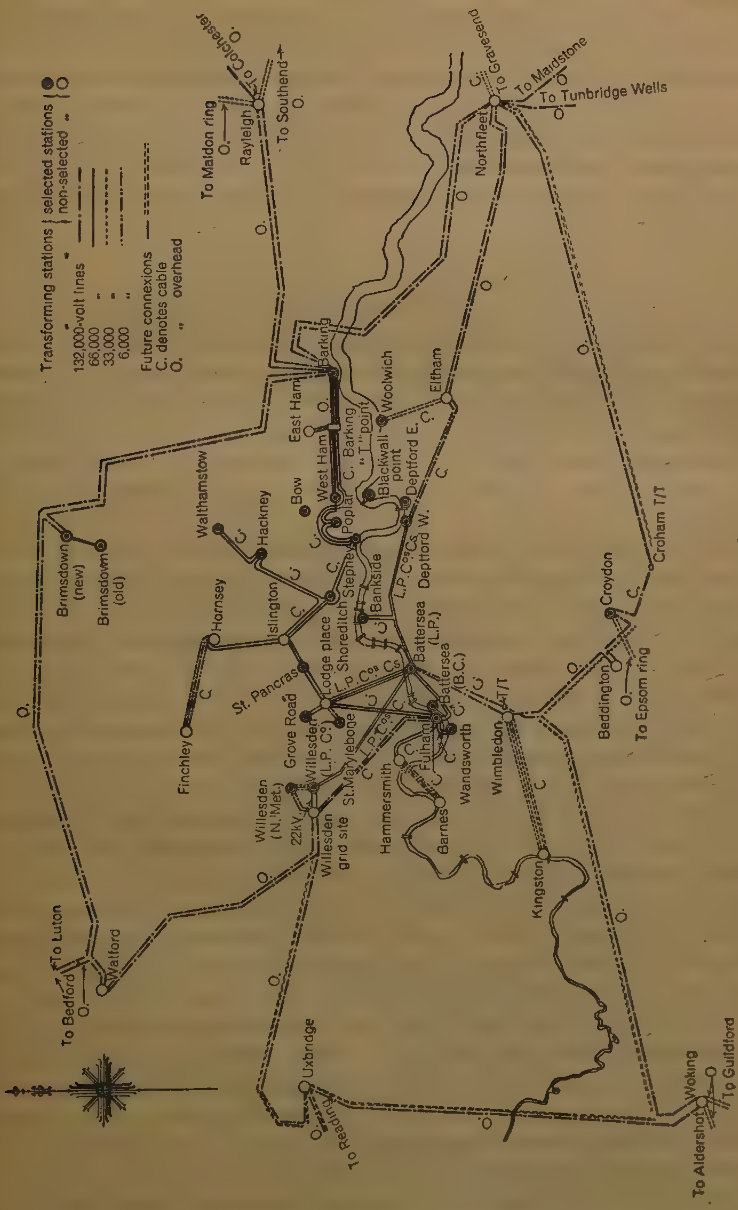
The continuous indication of a number of meters over a single pair of lines is novel. The indication of each meter is transmitted at a different frequency. A certain range of frequencies can be used for this purpose, and each meter is allotted a certain band within this range, the only limit to the number of meters being the number of such bands that can be accommodated in the given range. Each transmitting meter, instead of having a moving pointer, has a screen that moves over the dial of the instrument in such a manner that one segment of the dial is uncovered and the remaining segment is screened, the relative extent of the uncovered and screened segments depending upon the meter-reading. The dial is continually "searched" by a moving light-beam directed on to a light-sensitive cell. The track of the light-beam over the dial passes over a metal "comb," the width and spacing of the teeth determining the frequency of the current generated by the light-sensitive cell and used for the impulses of the particular meter. The duration of the impulses and the duration of the intervals between them are decided by the relative amounts of screened and unscreened dial. Each receiving instrument responds to one particular frequency only, and it adjusts itself in accordance with the proportions of the impulses received at this frequency. The reading of the receiving meter depends solely on the proportions of the impulses, so that the signals are not affected by variations in transmission-losses.

Associated with the supervisory equipment, and using the same two pairs of wires, is a telephone-system connecting the Fulham power-station with the Bankside control-room. A routine-instruction telegraph is also provided.

The Fulham control-room attendant is also connected by a telegraph-system to the boiler-house and to each of the turbines, so that he can transmit routine instructions in regard to the running of the plant in a minimum of time. This telegraph is supplemented by a loud-speaking telephone equipment for instructions of a more special nature.

In addition to his electrical functions, the control-room attendant is given remote electrical control, for use in emergency, of certain main steam-valves. The steam-valve emergency control-panel is enclosed in a glass case; by the operation of the appropriate push-buttons steam supplied can be cut off from various sections. This emergency control

Fig. 21.



INTERLINKING OF FULHAM POWER-STATION WITH SOUTH-EAST ENGLAND GRID.

does not, however, allow the control-room attendant to open valves. To guard against the inadvertent operation of any push-button the movement is one of both pushing and twisting. This panel has been placed in the control-room, as in an emergency, such as a burst, a serious blowout, or an oil fire near the turbine, it would be impossible for men to approach the valves to close them manually. It is under such conditions that the remote control would be utilized.

Fig. 21 (p. 59) shows the interlinking of Fulham with the South-East England Grid system.

Fire-Protection.

Fire-protection is of the utmost importance in a power-station owing to the large quantity of oil used for insulation and other purposes, which is liable to be fired under fault-conditions. The main problem is the protection of the main switchgear, which is the bottleneck through which the whole supply has to pass. The difficulty of this problem is increased when the station is connected to a large transmission-system, such as the Grid.

The first and primary protection adopted at Fulham, therefore, was to localize the effect of any fire by dividing the main switchgear into sections, each section being housed in a separate fireproof building. The switchgear is arranged so that only one alternator-switch and one feeder, out of any pair to a district, are situated in each section. The completed station will have five such separate switch-houses. All connexions and busbars for power-supplies brought into the switch-houses are insulated with bakelized paper and wire-armoured. All multicore cables for switch-operation are run as separate routes in a separate tunnel across the ends of the switch-houses, and divided therefrom by fireproof doors. Multicore cables, however, have to enter each section, and experiments are now being carried out with a view to protecting these multicore cables, where they rise to the switches, with at least a 1-inch covering of asbestos compound, moulded on to the multicore cables whilst in position. Where cables go through floors, special steps are taken to prevent the leakage of oil through such holes, based on the assumption that in the event of a fire the cable would be melted through and would tend to drop through the hole, leaving a space through which oil could pour. The cable is supported below the floor and a slab placed below the hole to form an enclosed box, below, which is filled with sand. Above the floor-level is built a brick chamber around the cable, which is again filled with sand. The sand is burned, as ordinary sand contains too much moisture.

The system of division is also carried out in the cable-basement, so that feeders going to the same destination are divided in separate chambers and are kept divided even in the tunnel to the Central Electricity Board's substation, situated at the far side of the site. The tunnel is built as two

entirely separate chambers, and both power-cables and pilot-cables are divided between the two tunnels.

The auxiliary switchgear, whilst not being in separate houses with an intervening air-space, is separated by walls with fireproof doors for the various sections.

Whilst the switch-houses in general are of fireproof construction, ample window-space has been provided in the form of roof-lights at the top of the houses, as experience has shown, even with relatively small switchgear, that explosions can completely wreck a building unless some form of safety-valve is provided. The quenching methods adopted for use in the event of fire in the main switch-houses employ carbon dioxide. Pipes are run throughout the switch-houses, and are connected to a main bus running to a bank of a hundred and sixty-two carbon-dioxide cylinders containing 12,960 lb. of gas. These cylinders are situated in the cable-basement, well away from the switch-houses, and are maintained at a temperature well below 88° F., which is the critical temperature of carbon dioxide. Each switch-house is provided with temperature-indicators worked by bi-metal strips. On the occurrence of an increase in temperature above 180° F., these operate indicating lamps and an alarm-bell on a fire-control panel situated in the control room. A check system is incorporated to indicate whether men are working or not in the switch-houses. The carbon dioxide is admitted by the control-engineer. Similar protection is also incorporated in the cable-tunnels and in all main-transformer chambers.

In the auxiliary control-room, where the whole of one side of the switch-houses is of glass, the "Mulsifyre" system has been installed and works off a common pressure-pipe supplying Mulsifyre fire-protection to other scattered auxiliary switches throughout the building, to turbine oil-pipes and to oil-reservoirs. Successful operation of the Mulsifyre equipment depends upon the automatic operation of a booster pump to maintain the pressure; this pump has therefore been provided with a direct-current motor worked off the battery, in case the whole of the auxiliary alternating-current supply should fail.

Considerable discussion has taken place from time to time regarding the relative advantages of inert gases and of methods utilizing water for the fighting of electrical fires. It is perhaps within the scope of this Paper to give consideration to the principal points involved, in the hope that it will bring to light other experiences and enable some conclusion to be drawn.

Inert gases have the advantage of putting out a fire practically instantaneously, without the disadvantage of considerable damage and dislocation, which is very often experienced with the use of water. However, there is reason to believe that, whilst inert gases will subdue a fire by reducing the proportion of oxygen present, if the fire has been severe it may again break out when the concentration of the inert gas falls below a

certain figure, because the gas has had very little cooling effect. In addition, there is the probability that an explosion can take place if a proportion of air is admitted to the building. Against this argument can be advanced the theory that the fire is extinguished immediately it starts, so that no very great amount of heat will have been generated. In practice, however, for various reasons the gas may not be applied until the fire has become well established. A further consideration is that a switchgear-building must be designed, as stated previously, with an adequate area of windows or laylights as a safety-valve. If, as anticipated, those windows were blown out by an explosion, the fire which resulted from the explosion would create an upward draught which might prevent the attainment of an adequate concentration of inert gas. It would, therefore, be interesting to carry out tests covering these two conditions, namely, that a fire be allowed to burn before the inert gas is applied for a long enough period to heat up the surrounding structure and that the equivalent of a chimney-outlet be provided at the top of the building. The Authors hope, with the co-operation of certain manufacturers, to make such a test in the near future.

The systems utilizing water depend upon the theory that a film of oil-and-water emulsion is spread over the whole surface, which excludes all air and puts out the fire. These systems undoubtedly work, and work with amazing rapidity. Further, the volume of water utilized is remarkably small, being measured in tens of gallons for a fire of quite large dimensions. The Authors are, however, doubtful whether the theory ascribed to these systems is really correct, as the intense heat at the seat of a fire would probably vaporize the water immediately on contact, so that a film could not possibly be formed. They feel that a more probable theory is that water broken up into a fine spray and projected at high pressure directly at the seat of the fire lowers the temperature to such a figure as to prevent combustion continuing. Whilst this theory may or may not be correct, it can be stated definitely that a fire put out by water will not re-start.

Dealing further with the probable reason as to why high-pressure atomized water systems put out oil fires, the Authors had the advantage of discussing with Continental engineers and testing for themselves the systems employed on the Continent.

As a result of experience and many experiments Continental engineers have, in a number of cases, departed entirely from the use of inert gases or of automatic and complicated systems utilizing water, and have gone back to the use of an ordinary hose worked off the fire main, but fitted with a diffuser-nozzle. This diffuser-nozzle projects the water in the form of a hollow cylinder, thus reducing the cross section of the water to a low figure. On first attacking a fierce fire the diffuser-nozzle is adjusted to project a parallel hollow jet of water, in order that the fire can be fought from a safe and more or less comfortable distance, and the water is used

solely with the idea of reducing the temperature at the seat of the fire. As the fire becomes less, so the diffuser-nozzle is adjusted to spray the water out into the form of an umbrella, and the fire-fighter approaches closer to the fire until he can direct the umbrella of water immediately over the seat of the fire and smother it.

Fire-fighting with the diffused jet is carried out without the necessity of making dead any plant, and it is interesting to note the distances at which men can work with perfect safety on live apparatus, as shown in Table IX.

TABLE IX.—MINIMUM DISTANCE IN METRES BETWEEN THE NOZZLE AND THE LIVE CONDUCTORS FOR VARIOUS VOLTAGES TO EARTH AND VARIOUS NOZZLE-DIAMETERS.

Voltage to earth of live conductors.	Diameter of orifice of nozzle.			
	34/34·6-millimetre spray-jet of variable area with optimum aperture.	7 millimetres.	18 millimetres.	30 millimetres.
115 alternating	0·50 metre	0·50 metre	1·00 metre	2 metres
460 direct	0·75 ,,	0·75 ,,	3 metres	5 ,,
3,000 alternating	1 ,,	2 metres	5 ,,	10 ,,
6,000 ,,	1 ,,	2·5 ,,	6 ,,	12 ,,
12,000 ,,	1·20 ,,	3 ,,	6·5 ,,	15 ,,
60,000 ,,	1·50 ,,	4·5 ,,	12 ,,	22 ,,
150,000 ,,	2 metres	6 ,,	15 ,,	25 ,,

NOTE :—

(a) If water is being applied downwards in a vertical or almost vertical direction, the values given in this Table should not be used because, with a very low pressure, the jet could be compared with a rod of water, and its impedance would therefore be greatly reduced.

(b) These figures are for water with a resistivity of approximately 3,000 ohms per centimetre cube, whereas that of English water may be as low as 2,100 ohms per centimetre cube. Revision of this Table would be necessary for each particular condition of water-supply.

The Authors have satisfied themselves that this is not mere theory by carrying out tests themselves, playing water on to a metal plate charged at 12,000 volts from a distance of 48 inches with a spray-jet. This test was carried out without any earth-connexion to the hose pipe, though normally the hose is provided with a strong flexible earth-connexion along its whole length.

The matter is of such interest that experimental plant is being prepared at the Fulham station for carrying the tests further. It is hoped at a later date to be able to provide considerably more information. If the results of the tests are as anticipated, it would seem to indicate that the provision of full automatic fire-protection, which is very costly, can be eliminated in many places and reserved only for vital key-points, where instantaneous action is necessary and where there is the possibility of

operators not being in constant attendance; for all ordinary fire-fighting for auxiliary switchgear, transformers, turbine oil fires, etc., it appears that ordinary hoses for the firemen, with the special diffuser-nozzles, would meet the situation just as effectively and would be considerably cheaper.

Cost per Kilowatt Installed.

As the Fulham station is not yet complete, it is not possible to give an official figure of the final cost. Table X, however, indicates the costs of the station at its present installed capacity of 190,000 kilowatts; in computing the cost of land and of circulating-water works, allowance has been made for the fact that they suffice for the final requirements of the station.

Table X.

Section.	Cost: £ per kilowatt installed.	Percentage of total expenditure.
Sub-structure	1·192	5·45
Superstructure	4·340	19·85
Circulating-water system	0·631	2·89
Coal-transport and attendant facilities	1·330	6·1
Land	1·885	8·64
Coaling plant	0·427	1·96
Steam-generating plant and mechanical plant	7·080	32·3
Electrical equipment	1·934	8·86
Gas-washing plant	1·282	5·85
Cost of loans, interest, engineering fees	1·730	7·92
Miscellaneous items	0·039	0·18
	21·870	100·00

Table X represents all items in the erection of the Fulham base-load station, but in comparing the installed cost per kilowatt with that of a normal station due consideration must be given to the fact that the capital costs stated include the following items:—

	£ per kilowatt installed.
(*a*) Air-raid precaution measures	0·263
(*b*) Provision of four sea-going colliers for the transport of coal	0·791
(*c*) The installation of gas-washing plant	1·521
(*d*) Housing for transmission-switchgear	0·295
	2·870

This figure deducted from the total given in Table X makes a final installed cost of £19 per kilowatt for a normal station of 190,000 kilowatts.

It will be noted the figure of £1·521 is given above for "gas-washing plant," as against £1·282 in Table X. The explanation of this is that

the figure given in Table X is the cost of the gas-washing plant only, whereas in estimating the second figure allowance has been made for the increased structural cost of the building to house the gas-washing plant.

Station-Performance.

The station now described has been in operation for a period of over 12 months with two 60,000-kilowatt sets, and for the last few months with three 60,000-kilowatt sets.

Table XI gives the performance for a year's working with two sets, and Table XII gives the best month's working achieved so far with three sets.

Table XI.

January to December, 1937.

Maximum demand supplied from station	121,800 kilowatts.
Total output of station	584,448,810 kilowatt-hours.
Time during which station was in commission	8,760 hours.
Yearly load-factor of station	54·6 per cent.
Load-factor of plant	67·7 ,, ,,
Average gross calorific value of coal	12,776 B.Th.U. per lb.
Heat-consumption per unit sent out	13,278 B.Th.U.
Coal-consumption per unit sent out	1·0393 lb.
Average overall thermal efficiency	25·689 per cent.
Total works cost	0·1444*d.* per unit.

Table XII.

January, 1938.

Maximum demand supplied from station	142,600 kilowatts.
Total output of station	77,958,000 kilowatt-hours.
Time during which station was in commission	744 hours.
Monthly load-factor of station	77·96 per cent.
Load-factor of plant	64·2 ,, ,,
Average gross calorific value of coal	12,820 B.Th.U. per lb.
Heat-consumption per unit sent out	12,995 B.Th.U.
Coal-consumption per unit sent out	1·0137 lb.
Average overall thermal efficiency	26·256 per cent.
Total works cost	0·1396*d.* per unit.

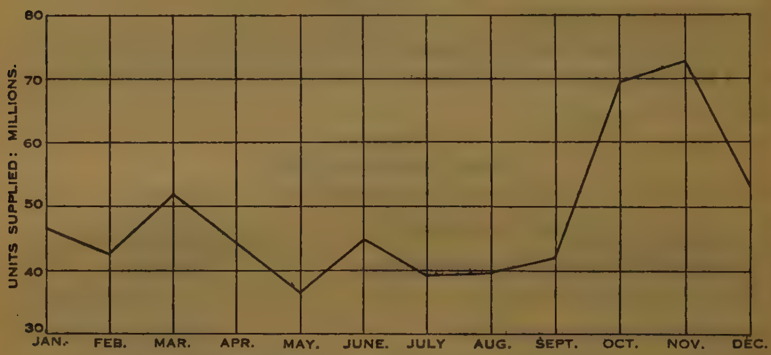
In each Table is given the total works cost (covering total costs of fuel, lubricating-oil and water, salaries and wages, and repairs and maintenance) with the corresponding performance-figures, which, it will be noted, are given on units sent out and not on units generated. It should also be remembered when comparing these figures that for over half the period under review the station was in the process of building-up to its full capacity. *Fig. 22* (p. 66) shows the units supplied during the year under review, and demonstrates that the station was working far from its full

capacity during that period. There is every anticipation, therefore, that the figures given will be materially improved upon in succeeding years.

The estimated total works cost for the first year's running was 0·1497*d.* per unit.

In the above figures are included the cost of sulphur-extraction as described in the Paper, and from careful records taken it can be safely

Fig. 22.



UNITS SUPPLIED DURING THE YEAR 1937.

assumed that up to date the cost of sulphur-extraction is approximately 10 per cent. of the total works cost. The year's total cost being 0·1444*d.* per unit, the sulphur-extraction has cost 0·0144*d.* per unit.

ACKNOWLEDGEMENTS.

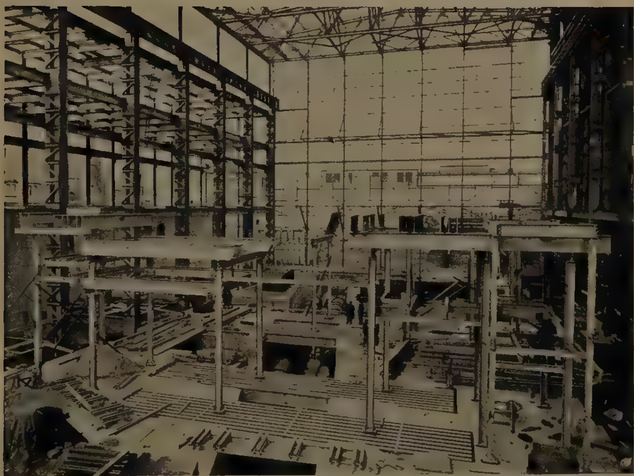
The Authors wish to express their full acknowledgement of the assistance and collaboration given by the Joint Consulting Engineers, Messrs. Preece, Cardew & Rider and Mr. Arthur J. Fuller, and to thank the members of the Fulham staff, who have so willingly collaborated in the collection of data. They also wish to express their appreciation of the assistance given in the loan of drawings, etc., by those who have been associated with the power-station.

The Paper is accompanied by thirty-one drawings, from some of which Plate 1 and the Figures in the text have been prepared, and by eleven photographs.

Fig. 23.

UNDERSIDE OF JETTY.

Fig. 24.



TURBO-ALTERNATOR FOUNDATION STEELWORK DURING ERECTION.

Fig. 25.

GAS-WASHING UNITS DURING ERECTION.

5172.
5171.

Fig. 26.

BOILER AISLE.

Fig. 27.

TURBINE-ROOM, SHOWING HOUSE SET AND THREE MAIN SETS.

Discussion.

Mr. J. F. Hay showed a number of lantern-slides illustrating the constructional work described in his Paper. *Fig. 23* (facing p. 66) was a view of the underside of the jetty, and showed the crane-girders, portal-beams, and subsidiary beams; it gave a good idea of the strength of the jetty.

Mr. W. C. Parker, in introducing the Paper by Mr. Clarke and himself, showed a series of lantern-slides, some of which illustrated the original power-station as built in 1901. He commented on the difference in the steam conditions and thermal efficiency over the intervening period of approximately 37 years, and stated that the thermal efficiency in 1901 was approximately 11 per cent. whilst in 1938 it was approximately 29 per cent.

Fig. 24 (facing p. 66) was an interior view of the turbine-room, indicating the steel framing for the concrete foundation of one turbo-alternator set.

Referring to the gas-washing plant, *Fig. 25* (facing p. 66) was a view of the plant in the course of construction at the +90 O.D. level. In a Paper embracing the whole of the activities of a power-station, such as Fulham, it was impossible to give any considerable amount of detail on any one item, but further details of the gas-washing plant could be obtained from a Paper by Messrs. J. L. Pearson, G. Nonhebel, and P. H. N. Ulander.[1]

The boiler aisle, which would be one of two in the completed station, was shown in *Fig. 26*, and he would draw attention to the unique design of the boiler control-panel. The turbine-room, completed for the first extension, was shown in *Fig. 27*. The temporary end in readiness for the next extension could be clearly seen from the photograph.

Mr. J. H. Rider remarked that, as one of the consulting engineers responsible for the design of the power-station, it would not be proper for him to attempt to discuss the Papers in the ordinary way. Owing to limitations of space, the Authors had only been able to deal with certain aspects of the station, but they had presented them extremely well.

The site of the station was by no means a convenient one, as it was divided into two parts by a refuse-destructor, so that the area available for the power-station proper had been limited. The station had had to be designed to the satisfaction of the Central Electricity Board, the Electricity Commissioners, the London County Council, the Ministry of Health and the Office of Works, as well as the Fulham Borough Council, and the station buildings had had to be stepped up from Townmead road to the top of the boiler-house, to avoid interfering with ancient lights.

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[1] Footnote (1), p. 31.

He would like to mention some of the outstanding points of interest in the station. With regard to the sulphur-extraction plant, it was quite simple to wash the sulphur out of furnace-gases, but very difficult to get rid of the washing liquor after it was finished with. At Fulham it could not be returned to the river Thames except under very onerous conditions, and Dr. Lessing had suggested that a circulatory non-effluent system should be used. When that system had first been tested in practice, however, it had been found that the gas-washers quickly became choked up with sulphates and sulphites. Dr. Lessing had then worked out the very ingenious method of preventing the formation of deposits on the grids, without which the non-effluent system could not have succeeded.

The Fulham station was, he believed, the first to adopt automatic superheat-control, which had proved most successful. Fulham was also, he thought, the first large station to have its main switchgear installed in separate isolated buildings, so as to minimize fire risk. In the switchgear itself duplicate tie-bars had been adopted, again, he believed, for the first time. If all the alternators in a station had to be paralleled through one tie-bar, any failure or accident on that tie-bar would prevent their running in parallel. The provision of duplicate bars made it possible to change over at once on to the other bar if the one should fail. The main step-up transformers were placed in fire-proof buildings separate from the station, and those transformers which were in the station itself were all air-cooled, to prevent risk of oil fire. Fulham was also one of the first power-stations to adopt simple axial-flow pumps for condensing-water circulation; they almost fitted into the pipe-line, and were highly efficient.

The working results of the first year were set out on pp. 65–66; from *Fig. 22* would be seen the very poor load obtained during that period. The wide variations of output accounted to a large extent for the relatively low thermal efficiency of only 26 per cent. He was sure from his knowledge of the station and of the men who operated it that, given equal loading and equal load-factor, the Fulham power-station would show results as good as those of any station in Great Britain. The results depended more than was sometimes realized on the station staff, and he would like to mention Mr. Priest, Mr. Scott, Dr. Francis, Mr. Hutchinson, and Mr. Gleave, some of the men who day by day carried on the work of operating and maintaining the station and obtaining the best results. He could not conclude without referring to those who had been concerned with the building of the station. Sir Harley Dalrymple-Hay and Messrs. Mott, Hay, and Anderson had been referred to in the Papers; they had been in charge of the foundation-works, tunnels, and jetty. Messrs. S. H. White & Son had been associated with them in connexion with the design of the structural steelwork and the erection of the buildings. Mr. Clarke, one of the Authors, had acted in a most loyal and efficient manner as Resident Engineer throughout the construction of the station. To the gentlemen he had

mentioned and to all who had been associated with the work he gave his hearty thanks.

The President remarked that there were one or two remarkable features of the station to which Mr. Rider had not referred. The most admirable characteristic of the coaling plant and of the stokers was that they were designed to deal with coals of very widely varying characteristics. The gas-washing plant had proved to be so efficient that no existing recording plant had been able to detect the amount of sulphur remaining in the chimney-gases, and a special recorder had had to be developed.

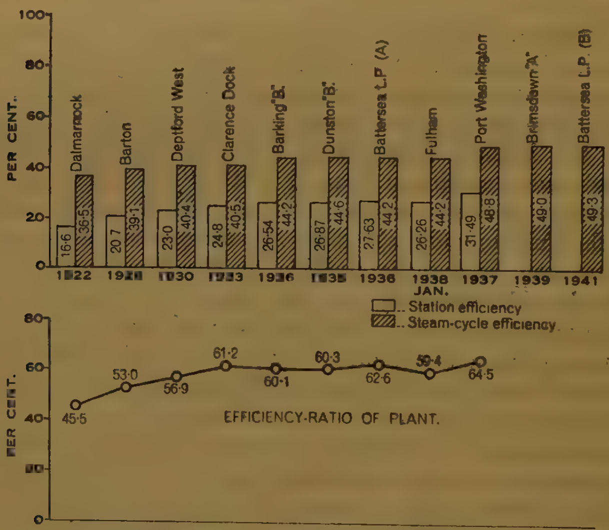
The detailed performance-data given on pp. 65–66 were very useful; their value would be enhanced if the Authors would state the average cost of coal fed to the bunkers during the two periods referred to in the Tables.

Mr. Johnstone Wright drew special attention to a feature which had not been brought out in the Papers, namely, that the station, which had an installed capacity at present of 190,000 kilowatts and would ultimately have an installed capacity of 310,000 kilowatts, had been built for the Fulham Corporation, whose electricity-undertaking last winter had had a maximum demand of 17,340 kilowatts. It would be seen, therefore, that the station had been built to supply not only the needs of the Fulham undertaking but also the greater load in the London area. That had been made possible by the general co-ordination of generation brought about by the 1926 Electricity (Supply) Act, under which the Central Electricity Board had been set up. Up to the present, the maximum demand of authorized distributors within a radius of 10 miles from London Bridge had been 1,600,000 kilowatts, and by 1941 it was estimated that it would reach 2,000,000 kilowatts.

The steps taken at the Fulham station to avoid atmospheric pollution were interesting, and those responsible were to be congratulated on the results. In addition to Dr. Lessing, Mr. Rider himself had put in an enormous amount of work on the problem. There could be no doubt that the sulphur-extraction problem had been solved both at Battersea and at Fulham, but in that pioneer work there had naturally been "teething troubles" to face. Mr. Wright believed that the methods in use were open to improvement, and that the engineers who were studying them would develop better and cheaper methods. In that connexion, he would draw attention to the costs given in Table X, p. 64, which showed that the gas-washing plant was responsible for increasing the costs of the station by over 30*s*. per kilowatt; the operating costs were also heavy. Where economics fixed the site of a station in a densely-populated area, there was no doubt that sulphur-elimination was necessary both from the point of view of health and from that of the preservation of buildings. It was to be hoped, however, for the sake of cheap electricity, that the fact that a method of sulphur-elimination had been found would not lead to an indiscriminate demand for its application in positions where there

was no risk of danger to health or damage to buildings. Dust-extraction was quite another matter, and he thought that provision should always be made for that. Table V, p. 35, emphasized the point (which had been brought out in several official reports) that the greatest sinner in regard to sulphur pollution was the ordinary domestic fire, manufacturing processes other than the generation of electricity being next in importance. A pure atmosphere was indisputably desirable, but, as a supply engineer, he could not see why the electrical industry should be singled out to lead the way at very considerable cost when other industries and other users of fuel were allowed to pollute the atmosphere without restriction, even when they were in direct competition with the electricity-supply industry.

Figs. 28.



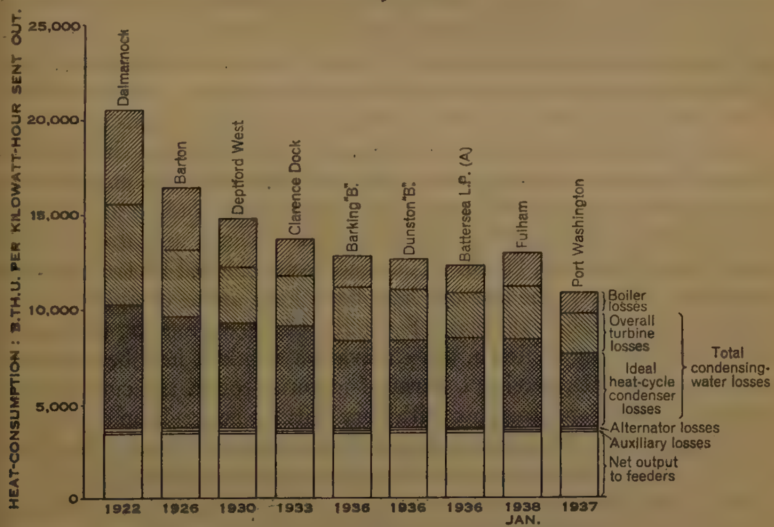
PERFORMANCE OF STEAM POWER-STATIONS.
(Based on Electricity Commissioners' returns and other published data.)

He hoped that before long the Minister of Health would distribute his attention a little more evenly.

The figures given in Tables XI and XII (p. 65), particularly those relating to thermal efficiency and coal-consumption, were of considerable value, and it was most interesting to trace the improvement in thermal efficiency and reduction of coal per unit during the past 20 years. He had made an analysis over the past few years of the performances of stations which had taken the leading places in the Electricity Commissioners' returns. *Figs. 28* showed for each of those stations the theoretical efficiency of the steam-cycle that had been adopted, and also the actual station-efficiency that had been obtained during one of its early years of operation. It would be seen that in 1922 the Dalmarnock station

of the Glasgow Corporation employed a steam-cycle with a theoretical efficiency of 36·5 per cent., and obtained an actual efficiency of 16·6 per cent., whereas in 1936 the steam-cycle efficiency of the Battersea "A" generating station was 44·2 per cent. and its actual efficiency 27·63 per cent. Still better figures had been obtained at Port Washington in the United States, and were hoped for from the new stations being installed at Brimsdown and Battersea. The graph in the lower part of *Figs. 28* showed the percentage ratio between the station-efficiency actually obtained and the theoretical efficiency of the steam-cycle adopted; it demonstrated that steady progress was being made not only in the steam-cycles adopted but also in the individual details of the plant, enabling stations to operate

Figs. 29.



PERFORMANCE OF STEAM POWER-STATIONS.

(Based on Electricity Commissioners' returns and other published data.)

at an efficiency much nearer to the theoretical maximum than had been the case in the past. That was perhaps more clearly shown in *Fig. 29*, which illustrated the allocation of the heat-input to the station per kilowatt-hour sent out. It would be seen that the greatest improvement since 1922 had been in the reduction of boiler-losses; the performance of the turbines and condensers had also been improved, but to a lesser extent. He did not consider it fair to include the 1937 figures for Fulham in *Figs. 28* and *29*, as during that year the station had had a poor load. For purposes of comparison, however, he had inserted figures based on the Fulham results for January 1938 taken from Table XII.

Dr. David Anderson said that, like Mr. Rider, he could not criticize his own work, and he did not want to touch upon the constructional

engineering details as his partner, Mr. Groves, who had been chiefly responsible for the work, would deal with those. The presentation and discussion of Papers, however, was a means by which engineers could pass on their experience to others. He had therefore asked himself: "What experience have I gained in connexion with this work?" and he thought that the sinking of the jetty-caissons deserved mention. He had sunk many caissons, particularly for bridges, but at Fulham he had been faced with a novel problem. The jetty had to be built just outside a very light and heavily-surcharged river-wall founded on ballast, and he wanted to carry the foundations down into solid clay. Various methods were considered, and finally it was decided to use fourteen caissons. They had to be sunk to −20 O.D., whereas the foundation-level of the old wall was about −8 O.D. In the sinking of caissons, however, sideways movement or "draw" was very apt to occur. Very often an inch or two one way or the other made no difference, but at Fulham it was essential that no lateral movement towards the river should take place, as the old river wall would have followed it, and might have collapsed and interfered with the use of the existing generating station. When the caisson-sinking work had been put out to tender, one of the tenderers told him emphatically that he was attempting the impossible, but he was glad to say that all fourteen caissons had been successfully sunk without any draw by the method described on pp. 11–13. That had been achieved by two principal precautions. Firstly, the caissons had been kept under complete control until they were well into the clay. Secondly, before exhausting the air in a caisson and blowing it down, the excavation inside it had been concentrated in the middle, leaving a berm of material round the cutting edge. Those two precautions, together with very faithful supervision on the part of Mr. F. E. Pryor, the agent in charge of the work for Messrs. Peter Lind, and of Mr. Hay, had been responsible for the result achieved.

Mr. J. M. Kennedy observed that on p. 17 Messrs. Parker and Clarke stated that the Fulham station, when completed, would be the largest municipally-owned base-load station in Great Britain; but perhaps it should be mentioned that in a few years' time it would be surpassed by the Hams Hall station of Birmingham, whose capacity was to be increased to about 500,000 kilowatts.

He would like to associate himself with other speakers in paying a tribute to all who had been concerned with the gas-washing plant, which had exceeded expectations and had achieved marvellous results; its cost, however, was very high. Taking capital charges at $6\frac{1}{2}$ per cent., the annual cost appeared to be about £19,000 for capital charges and £35,000 for operating costs, a total of approximately £54,000; on a coal-consumption of approximately 270,000 tons, that represented an addition of 4*s*. per ton of coal for the privilege of not defiling the atmosphere. As Mr. Johnstone Wright had said, it was desirable and indeed necessary not to defile the atmosphere, but if that could be achieved only at such a high cost it was

to be hoped that other coal-users would be subject to similar restrictions. No doubt the Authors would refer in their reply to any methods which they were attempting to use in order to reduce the cost; he had heard that they were at present testing certain alterations. Had they considered whether it might be advantageous to use electrostatic precipitation before the gas-washing plant, so as to reduce the amount of material that had to be dealt with in the scrubbers?

Precautions against fire were dealt with very well on pp. 60–64. He was particularly interested in that subject, being Chairman of a Committee which the Electricity Commissioners had set up as the result of a disastrous fire at Bradford power-station. He was glad to see that the recommendations which the Authors gave agreed very closely with the report that the Committee was issuing.[1] There was one point where the Authors might be misunderstood; they appeared to suggest on p. 63 that fire-fighting with diffused water-jets could be carried out without the necessity of making dead any plant. He presumed that they were referring there only to a fire which was not in the electrical plant itself and not of an electrical origin; the Commissioners did feel, as the result of experience, that when an electrical fire occurred it was essential to cut off the current from the section affected at the earliest possible moment, and then to set about the fire-fighting work. He thought that Table IX (p. 63) should be attributed to the tests made by the Paris Fire Brigade and the engineers of the Paris Electrical Distribution Company.[2] It might be mentioned that insulators on the Central Electricity Board's lines were sometimes cleaned by water-jets without shutting down the circuits.

With regard to the overall costs of the plant and the working results, the overall cost per unit sent out had always to be borne in mind; in his opinion, it had still to be determined whether or not the high thermal efficiencies nowadays attained could be achieved at an economic price. *Fig. 30* (p. 74) illustrated that problem; the data shown on the curve had been calculated for a plant load-factor of 60 per cent., a coal-price of 17*s*. per ton (which was perhaps a little lower than that at Fulham), a calorific value of 12,500 B.Th.U. per lb. of coal, and capital charges of 6½ per cent. Taking the capital cost of plant at £15 per kilowatt, which might be regarded as a reasonable cost at which a normal station could be constructed, a normal thermal efficiency could be expected of about 25 per cent. on the units sent out. If it were desired to raise the efficiency to about 28 per cent., the change would only be worth while if the capital cost were not increased by more than about £3½ per kilowatt. He desired to emphasize that point, because the question of overall

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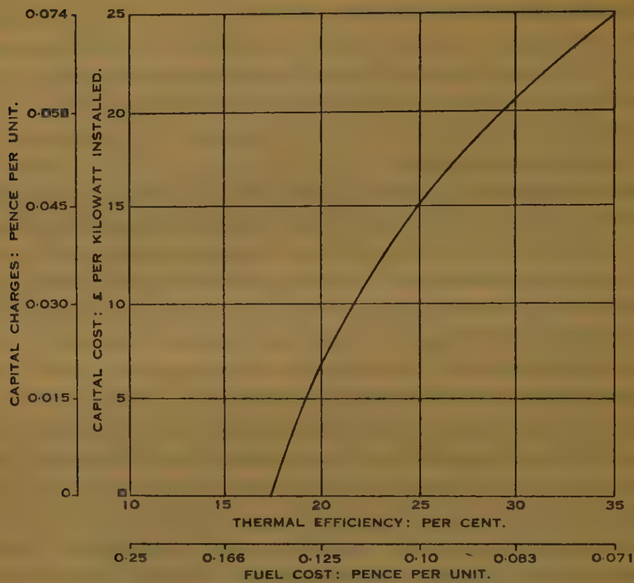
[1] "Fire Risks at Generating Stations." H.M. Stationery Office, 1938.

[2] Yves Le Moigne, "Les moyens de combattre le feu dans les installations électriques à haute tension (centrales, postes, et sous-stations)." Conférence Internationale des Grands Réseaux Electriques à Haute Tension, Paris, 1937. (Paper No. 319.)

Fig. 30.



THE COST OF EFFICIENCY.

economic efficiency should not be overlooked in the search for higher thermal efficiencies. Admittedly stations such as Fulham started with a handicap of heavy site costs, but he still thought that his argument applied.

Mr. G. L. Groves remarked that on pp. 3–4 Mr. Hay referred to the extraordinarily uniform level of the London clay over the site of the power-station. That had been very convenient, but he would like to mention in passing, as a warning to others who might hope for a repetition of the good fortune experienced at Fulham, that in a recent piece of riverside construction upstream of the coaling-jetty untold annoyance and trouble had been experienced by reason of the variations of the clay-level over a short length.

The coaling-jetty had cost approximately £3 10*s*. per square foot of deck area; that included the cost of the conveyor-gantry, which was virtually an upper deck to the structure, but it might seem a rather high figure. It was no doubt true that a jetty of cheaper type could have been erected, but he suggested that, in designing a coaling-jetty for a power-station costing some millions of pounds, it would not be reasonable to attempt to reduce expense to the bare minimum. A coaling-jetty in tidal waters was particularly liable to deterioration and damage, and the extra safety of a substantial structure was thoroughly worth a little extra cost. The rubber buffers described on p. 14 had been adopted because it was desired to avoid the use of steel springs, as steel was particularly

liable to corrosion and early deterioration in a riverside site. The use of rubber did not appear to have been mentioned previously in the Institution publications, although many types of fendering had been described. If anyone had had experience of rubber buffers in works which had stood for a longer period than Fulham power-station, it would be of interest.

Mr. Hay referred to the river intake-chamber as being a concrete structure with rolled-steel joists encased in concrete. The same type of construction had been used for the station intake-chamber and the river outlet-chamber. It might be preferable to call them steel-framed structures with a rich concrete added for protective purposes. The weight of steelwork used might have been rather greater than if a conventional reinforced-concrete design had been followed, but it certainly made the construction work more simple, and he thought the circumstances justified it. In those big dams, and particularly the river-intake dam with its mass of heavy timbering, the handling of quantities of reinforcement would have added considerably to the complications of the work.

In conclusion, he supposed that the work described, like any other great engineering work, would be taken very much for granted by the layman, but it could not possibly be taken in that way by anyone who had been associated with it. He had watched the station taking shape from the comparatively secure niche of the constructional side, and had been immensely impressed by the number and difficulty of the problems which the consulting engineers had had to tackle. In spite of all the difficulties that the consulting engineers had had to face, his experience, which he was sure was shared by all those associated with the work, was of an unfailing geniality and unruffled direction of the work by those responsible for its control and organization.

Dr. R. Lessing remarked that Mr. Rider's praise of the chemical development-work in connexion with the gas-washing plant was not entirely justified, because some of the decisions that had had to be taken had been actually forced by the mere consideration of the essential factors of the problem. The first important decision had been on the question of the non-return of the effluent into the river, it being taken for granted in the first instance that a wet washing process would have to be adopted. That decision had been made in the space of a few hours, a few days before the inquiry before the Electricity Commissioners began, on the receipt of the conditions of the Port of London Authority regarding the purity required in water to be returned to the river. On hearing those conditions, he had been very alarmed, but Mr. Rider had courageously accepted his suggestion that a cyclic circulatory system should be adopted. It had not then been possible to foresee all the consequences of that decision, as, although they had mainly to deal with such a simple and well-known chemical compound as calcium sulphate, the essential facts about it were then unknown. It was on account of that ignorance that when the washing work proceeded very smoothly, no difficulty being found in extracting almost 100 per

cent. of the sulphur from the gas, they thought that they were at the end of their labours; then, however, they were faced with the difficulty of incrustation of the plant. In order to overcome that incrustation and silting, the obvious thing that suggested itself was to reduce the concentration of the suspended solids in the washing liquor. The unexpected result of circulating a well-clarified liquor was that incrustation increased to such an extent that the plant was completely blocked after 72 hours. As the result of special researches, the problem was solved by increasing the suspended solids beyond anything that had previously been considered. Mr. Clarke would probably remember the first experiment of running liquor almost of the consistency of pea-soup through a small, quickly-constructed washer, when no incrustation occurred. Once that fundamental fact was recognized, the work became easier.

One point of an engineering nature that he would like to emphasize was that from the beginning it had been decided to subdivide the whole washing plant, and not to rely upon one single large plant for all the boilers. Every boiler was to be fitted with its own unit, and each unit was again to be subdivided into two halves, so that if need should arise to run a boiler on half load, one half of its washing plant could be shut down. That permitted of easy control of each boiler, and made it possible to adjust the travel of the gases and of the liquor in the best possible manner.

He would like everyone interested to consider the difficulties involved, particularly at the beginning, when no practical experience had been available, in treating about 750,000 cubic feet per minute of flue-gas containing roughly $\frac{1}{2}$ grain of sulphur dioxide per cubic foot, and extracting 96 per cent. of that sulphur dioxide, as was necessary under the conditions laid down. In point of fact, the figures given by the Authors showed that 99 per cent. could easily be extracted. Further, he would like to express the result of that extraction in figures which could be readily appreciated. With ordinary coal, sulphur in terms of sulphuric acid—into which it eventually turned—was present in the gases to the extent of 100 tons per day. The quantity discharged to the atmosphere was rather less than 1 per cent. of that figure—only about 1 ton. Mr. Kennedy and other speakers had referred to the question of atmospheric pollution. Obviously, in the first instance, when London had been faced with the possible construction of two super-power-stations pouring out sulphur at that rate, the position appeared to be very grave. In point of fact, the very danger which the proposal might have caused had led to an improvement, because with the washing plants now in operation the rate of emission of sulphur into the London atmosphere was being reduced by about 100 tons per day expressed as sulphuric acid in each case, as the power supplied from the stations replaced an equivalent coal-consumption in other appliances. In other words, one station like Fulham or Battersea reduced the total sulphur-emission over London by about 5 to 10 per cent.

Mr. A. C. Dean remarked that, since it was indicated on p. 18 that the

construction of the station had occupied more than 4 years, it would only be right to place on record, as he believed the case to be, that construction had advisedly proceeded slowly at certain stages of the work. It had previously been mentioned by him and by others that, if the work were reasonably fully planned before commencement, it should be possible to construct even so large a station as Fulham in from 21–24 months.

From experience in connexion with the reinforced-concrete jetty at the Battersea power-station [1] he had no doubt that the decision to construct the Fulham jetty on caissons was entirely sound. In 1928, prior to the decision to utilize the Battersea jetty as the intake-chamber, the following estimates had been made of the price per linear foot of jetty for various forms of construction : pile construction, £44 ; caisson construction, £48 ; pier construction, £84. The last-named had finally been adopted on account of the specific purpose to be fulfilled.

He was concerned at the detail given in *Fig. 1* (p. 5) of a typical retaining wall. The wall was about 6 feet thick and, although surrounded by interlocking steel piling, which had apparently given no anxiety on account of leakage, was further protected by both brickwork and asphalt. In view of the stratum of London clay at —12·0 O.D., the degree of protection appeared excessive, and he would be interested to hear more of the reasons leading to its adoption. It was stated on p. 6 that the raft-thickness was 12 feet, although in *Fig. 1* it was 8 feet, and from *Fig. 7* (p. 21) it appeared to vary between 8 and 12 feet. Those figures seemed high, unless it had been the case that no definite provision for the location of heavy stanchion-foundations and other loads had been made prior to the construction of the raft.

It would appear that the circulating-water tunnel diameters had been arranged to give a water-velocity of slightly under 5 feet per second. The linings (variously described as of Accrington or blue brick) had presumably been the basis of that decision. After considerable experience with the former brick as a lining, he was of opinion that for such a purpose a velocity of 7 feet per second was by no means excessive, and that some reduction in diameter might have been practicable if such a velocity had been thought permissible. At Battersea power-station, where shields had been used, it had been found economical to adjust the tunnel-diameters to the nearest sizes of shields available, namely those used in the London Underground. From information given on the drawings and in the text it would seem that if the intake-culvert had been sited a few feet deeper it would have been possible to obtain a much straighter run between the river inlet-chamber and the station inlet. If that were correct, between 150 and 200 feet run of construction would have been obviated and cut-and-cover work could have been carried out below the rafted area. The information in the Papers was not complete in that respect, and perhaps the Authors would kindly correct what might be a misunderstanding of the circumstances.

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[1] Minutes of Proceedings Inst. C.E., vol. 240 (1934–35, Part 2), pp. 74 *et seq.*

Reference was made on p. 20 to provisions made for wind-pressure. He did not think that any engineer would believe that wind-loadings were magically and tidily transferred through long stretches of buildings to the particular spots where convenient provision could be made to take them up. Power-stations not only had vast areas of heavy continuous floors which had no place in wind-load calculations, but they were tied together by subsidiary internal structures of various kinds, as a result of which it was impossible to calculate what happened to wind-loadings except by methods that were meaningless, and at the same time very expensive in result. In his opinion the stability of such buildings was far more liable to be disturbed by vibratory or excessive internal loadings than by wind-effects which in practice would be absorbed in the structure as a whole. So long as such buildings were subject to building regulations excessive provision of steelwork would remain necessary.

The Authors referred on p. 27 to induced-draught fans running out of balance; that effect was not unheard-of in circumstances not associated with gas-washing, and had sometimes caused considerable vibrations in the supporting structure. It had been his own practice for a number of years to design the supporting steel in relation to the critical speed of the fan-units, exactly as was ordinary practice for large turbine-foundations, reverting to purely statical design for the primary members of the general steelwork.

Mention was made (on p. 22) of protection of the concrete and reinforcement of the chimneys, but the provision made was not specified. Would the Authors state what had been done in each case and the measure of protection that had been achieved?

With regard to the general character of turbo-generator foundations, although he did not suggest that with the normal conditions available for efficient curing of concrete in initial constructions any trouble would arise, considerable cracking had been observed in large turbo-generator foundations that had been formed within existing buildings. In such circumstances shrinkage-cracking might be extensive, due to the difficulty of proper curing in a building already partly occupied by other plant and at a fairly high temperature. The normal foundation-block for sets of 25,000 kilowatts and upwards was a large mass structure with steel reinforcement in a quantity not necessarily proportionate to the static and dynamic loads to be carried. Residual stresses would exist in the concrete, whatever the method (continuous or intermittent) of pouring. Observations carried out in a foundation of that character under his supervision had shown a theoretical stress due to shrinkage amounting to 2,000 lb. per square inch remaining in the concrete $2\frac{1}{2}$ years after completion of the foundation at depths between 5 feet and 7 feet 6 inches from the face. He did not suggest that danger would necessarily result, but it was true that the conditions of stress existing in such a foundation were unknown. He was doubtful as to the value of continuous pouring (which was frequently recommended)

owing to the likelihood of undue temperature-rise, and he believed that the correct form of foundation would prove to be one having a framework basis with independent panelled fillings where required. He also advocated the removal of the stanchions carrying the steel platform on which the generator rested prior to concreting, in order to obtain a more determinable load-distribution. He should make it clear that his remarks were not in any way to be regarded as a criticism of the new Fulham turbo-generator foundations, which followed ordinary practice for an initial construction.

The costs in Table X (p. 64), as related to the ultimate station-capacity, appeared to give a total of about £8 per kilowatt for structural works, and that figure did not differ much from that for the Battersea power-station constructed a few years earlier. The degree of permanence of large station-buildings had often been discussed. He recalled that in 1924, when the Barton and Dalmarnock stations had been discussed at The Institution, Mr. Burnside had stated [1] that a 20-year limit should be prescribed for such building works, but the pendulum had actually swung the other way and buildings erected recently were apparently generally no less expensive per kilowatt than they had been 15 or 20 years ago. At the same time, it was only fair to appreciate that that was not the fault of the structural engineer, who had to provide a vastly increased footage of accommodation per kilowatt to suit plant requirements and had to offset that by improved methods of design and construction. None the less, he believed that in almost every station it would be possible to reduce building costs materially if a nearer approach to complete planning and co-ordination in civil, mechanical, and electrical works were obtained before construction commenced.

From p. 64 it seemed that a sum of about £50,000 had been expended in air-raid precautions. Were the Authors able to state whether any of that sum related to constructional works, and if so, could they briefly sketch the manner of its application for that purpose ?

Mr. W. M. Dodds observed that on p. 19 it was stated that the type of coal which the Fulham station used was controlled in the main by the requirements of stokers and conveyors, and that, as at least two base-load stations on the river Thames were similarly equipped in those respects, an increased demand was being brought about on the coalfields for a narrow range of their product, thus tending to create a shortage and a rise in price. Those statements might, however, lead to a far from accurate conception of the coal-burning capabilities of the stokers.

It would be apparent on reflexion that the siting of the station practically ruled out the use of coal from inland coalfields. Also, as the station was so far up the river as to preclude the possibility of colliers of more than 2,000 tons capacity being used, the cost of transport was not likely to be as low as it would be with larger colliers and it was thus

[1] Minutes of Proceedings Inst. C.E., vol. ccxviii (1923–24, part II), p. 402.

unlikely that it would be economic for the station to use coals of such high ash-content as might be used in stations which were able to receive bigger vessels. Again, as the Authors explained, the geographical position of the station had imposed restrictions with regard to the sulphur-content of the gases leaving the chimneys, which, in turn, had introduced the necessity for gas-washing and made it advisable to burn coal having a low sulphur-content and a high calorific value, thus minimizing the total sulphur in the gases and the consequent cost of extraction. With those fundamental or "station" restrictions in mind, it was apparent that the fuels economically available for Fulham would be those which were mined in the Welsh, Northumberland, Durham and Scottish coalfields and which would be available in quantities commensurate with the requirements of the station. It appeared from p. 24 that the coals which had been satisfactorily burned since the station started had widely-varying characteristics and had been obtained from each of the four coalfields mentioned. It did not therefore seem either that the stokers appreciably limited the characteristics of the coal used, or that the requirements of the stokers could be such as to create a demand for any considerably narrower range of coal than that imposed by what he had described as "station" restrictions. In order to emphasize that point he had estimated that the present rate of coal-consumption on Taylor retort-type stokers in Thames-side power-stations was 1,236,000 tons per year, and that that was taken up by each of the four coalfields in question as followed: Welsh 47 per cent.; Northumberland 17 per cent.; Durham 12 per cent.; and Scottish 24 per cent. That showed clearly that fuels from all those fields were burned with equal facility. With Welsh coal having as little as 13 per cent. volatile and Scotch coal up to 32 per cent. volatile, it was surely to the credit of the combustion-apparatus that it could satisfactorily use such a diversity of coal in the totally water-cooled combustion-chambers of the Fulham power-station. In fact, the use of low-volatile Welsh coal in a completely water-cooled furnace had been practically unknown amongst Thames-side power-stations prior to 1934, when the Taylor type of stoker was coming into extensive use; the stoker could therefore actually be credited with having widened rather than narrowed the coal market.

He felt, however, that any divergence of viewpoint between the Authors and himself in the matter was more apparent than real, and that the only point with which they were concerning themselves related more particularly to sizing. Dealing with that aspect of the subject, the Paper stated that if the amount of coal over ½ inch in size was less than 40 per cent. of the total, the station was then limited to the use of coals having not more than 40 per cent. of fines passing a ⅛-inch mesh, and that that restriction was even greater if the percentage of moisture in the fuel exceeded 12 per cent. He could not say for certain whether such restriction was caused more directly by apparatus which was not part of the stoker equipment but which might be closely associated with it, or whether it resulted from the function-

ing of conveyors or chutes, but he could state definitely that while the stoker might be the victim of some such restriction, it was certainly not the cause. Stokers of exactly the same design as those in the Fulham plant were, in at least two other plants, regularly burning fuels which had 55 per cent. of fines passing a ⅛-inch mesh and had probably not more than 16 to 20 per cent. over ¼ inch in size. Special stokers of similar type which had recently been constructed and installed for high-rating operation were equipped with a system of mechanically-operated feed-equalizers; on a recent test of such a stoker, coal with fines of 65 per cent. passing a ⅛-inch mesh and having as little as 10 per cent. over ¼ inch in size had been used satisfactorily. At the same time, lumps of 3 or 4 inches in size could be dealt with. Accordingly, he felt that it was just as incorrect for the Authors to state that the stokers were placing a size-restriction on the type of fuel used as it would be to claim that they were creating a demand for coal within a narrow range of chemical or thermal characteristics. In that connexion it might not be thought important to consider the successful use of large-sized coal, but in view of the artificially high price which small coal obtained at present, it should be remembered that the use of large-sized coal might well be more economic than was generally supposed.

In any event, if the Authors felt that it would be to their immediate advantage to burn finer coals than those which they were now using, he could assure them that there was nothing to prevent that course as far as the stokers were concerned. In fact, he believed that a proposal had been under consideration when the last two Fulham stokers were being installed to fit them with fuel-feed equalizers so that they could utilize an even finer coal if it were found possible and practicable to feed it to them. Ultimately, however, the idea had been dropped, and he believed that one of the considerations which prevented its adoption was the feeling that the use of very fine coal might militate against long service-hours being obtained from the gas-washing plant. Further, its use might create a public nuisance unless a relatively dust-free method of unloading, storing and conveying could be evolved. Many such factors had to be considered in connexion with the possible use of excessively fine coal for a plant such as Fulham. Apart from those factors, there was considerable doubt about the availability at economically advantageous prices and in adequate quantities of coals that would meet the "station" restrictions and, at the same time, would have sizing of such fineness as to be beyond the demonstrated capabilities of the stokers. Again, if such coals did exist, it would have to be considered whether or not arrangements necessary for their use might not actually defeat their own ends by introducing other serious restrictions.

In considering the question of coal-supply, it would be useful if the Authors could state what portion of the total works cost of 0·1444*d.* per unit as given in Table XI (p. 65) for the first year's running was fuel cost.

Mr. F. W. Matthews said that it was difficult to see from Mr. Hay's Paper why it had been necessary to excavate 13 feet of ballast down to the clay and to fill it back with concrete before starting the work proper, particularly as that concrete itself would probably put an extra load of about 1 ton per square foot on the clay. Only one typical section (*Fig. 1*, p. 5) was given for the retaining-wall; it was of reinforced concrete 5 feet thick, backed with steel sheet-piling, and to make it watertight it had been considered necessary to put in 9 inches of blue brick and $\frac{3}{4}$ inch of asphalt. Was the building completely enclosed by such a heavy wall? The weight of structural steelwork in the station was stated on p. 20 to be 21,000 tons. He wondered whether there were any particular points in the design or construction which necessitated what appeared to him a rather extraordinary tonnage of steel.

The circulating-water tunnels had all been constructed by normal methods with cast-iron segments, but he noticed that three different types of lining had been used, namely, blue brick on concrete, Accrington brick (it was not stated whether that had a concrete backing), and $\frac{3}{4}$ inch of gunite on concrete. He would be very interested if Mr. Hay would state why three different linings had been used and what results had been obtained.

Mr. P. H. N. Ulander remarked that on p. 27 it was mentioned that the induced-draught fans had given some trouble due to out-of-balance and to the erosive and corrosive action of the carry-over from the washers. In the same section it was stated that the fans were designed to be self-cleaning. The two statements, when read together, sounded slightly sarcastic. The troubles had arisen because the fans had had to be placed after the gas-washers, as the washers themselves were placed inside the building, and the danger of a leakage of carbon dioxide into the building precluded placing the fans between the air-preheaters and the washers. However, the station gained in one respect, in that with maximum continuous rating the power-consumption per boiler for the induced-draught fans was about 50 kilowatts less than it would otherwise have been, so that the thermal efficiency of the station was increased by about 0·06 per cent. That might sound very little, but it was worth having. As mentioned by the Authors, the difficulties were actually brought about by minute particles of about 5μ or less in size enveloped in water being deposited on the fan-blades. As the surrounding atmosphere was saturated with water, it was impossible for the water surrounding the particles to evaporate; a deposit was thus formed, and, when that deposit had grown sufficiently, parts of it were thrown off and the fans got out-of-balance.

With regard to the erosion and corrosion of the fan-blades, it should be kept in mind that the tip-speed of the fans when running at full speed was 15,000 feet per minute, and experience from pulverized-fuel-fired boilers showed that at that tip-speed even minute dust could have a highly

erosive effect; although corrosion might play some part in the trouble, it was no doubt erosion which had the greatest effect.

With regard to the cost of the gas-washing plant, which had been mentioned by other speakers, experience had shown that it was very difficult to reduce the capital cost of efficient gas-washing plant. The size of the essential parts of the washer, such as the space required for washing-chambers, liquor-circulating system, alkali-preparation and sludge-disposal plant, was not determined by the efficiency but only by the quantity of gas to be dealt with. Furthermore, in order to increase the reliability and to keep the maintenance-cost low, experience had shown that a more costly design was desirable. It was therefore possible that gas-washers in the future might be even more expensive than they had been in the past. The Paper might be thought to contain some faint praise but also some pointed criticism of the gas-washing plant. There was no doubt that the plant as delivered and started up could be criticized, but it had to be remembered that when the plant was designed the only actual operating experience available was from a comparatively small pilot plant at Billingham. It would have been easy to avoid the failures of rubber covering in the circulating-pumps if the order had been placed a few months later.

Mr. W. A. Damon questioned the statement on p. 29 that non-effluent gas-washing systems would be essential for all future power-stations on the Thames. Figures that had been published relating to the effluent from the Battersea power-station indicated that detrimental effects were not inevitable, and could certainly be avoided by the use of proper methods of treatment.

Since the Fulham plant had been put into commercial operation, problems had been continually arising, and, as the Authors had shown, they had been energetically tackled. The attempt to inhibit the oxidation of calcium sulphite to sulphate was especially interesting, as he believed that at one time it had been thought necessary to encourage that oxidation as much as possible. The problem at Fulham was almost entirely that of sulphur-dioxide absorption; with the type of stoker used, there could not be much dust passing through the washers, and it might be possible eventually to recover relatively pure calcium sulphite from the plant. It was possible that a process might be developed for the production of sulphuric acid from calcium sulphite, and much had been heard recently of processes for the concentration of sulphur dioxide and its reduction to sulphur. If the sulphur contained in the coal could thus be recovered and put to commercial use, the gas-washing process would at once become very much cheaper.

It was part of his duty to make tests to determine the acidity of the effluent gases at Fulham, and the average of the test-results in 1937 was 0·005 grain of sulphur per cubic foot of dry gas at N.T.P. That represented an efficiency of removal of about 99 per cent. It was truly remarkable that a modern power-station, producing vast quantities of energy which

could replace coal in the home, could itself burn nearly 500,000 tons of coal per year with no emission of dust or smoke and with no appreciable effect on the sulphur-dioxide content of the atmosphere. That great achievement was of the utmost value from the points of view of health and of the preservation of structures. At the same time, its cost was very great, and it might well be that even greater value would attach to a process cheaper in capital outlay and in cost of operation which would have a wider application, even if its efficiency were not quite so good. In that connexion, the importance of efficient methods for the removal of sulphur-bearing constituents from the coal before it was used should not be overlooked.

Sir George Lee, President I.E.E., on behalf of the Institution of Electrical Engineers, expressed their appreciation of the invitation to attend the Meeting. It was a move in the direction of co-operation between engineering Institutions, which many would like to see extended as much as possible. They would also like to join in the congratulations to the Authors of the Papers, which they had found very interesting and very instructive.

*** **Mr. Karl Baumann** observed that the Papers gave an admirable and concise description of a modern power-station. Those features that departed from usual British practice were naturally the most interesting; it would be of value if the Authors would indicate whether those departures had been justified in operation. There were certain points in which he was particularly interested. The Fulham station was one of a few in Great Britain where retort-type stokers had been adopted, although they were used to a very large extent in the United States of America. The largest boilers so equipped were those at the Hudson Avenue station in New York, where the stoker-area was 694 square feet for a maximum rating of 452,000 lb. per hour, which corresponded to a rating of 650 lb. per hour per square foot of projected area. At Fulham the area was 470 square feet for a rating of 260,000 lb. per hour, equivalent to 550 lb. per hour per square foot. In that connexion it was of interest to note that the latest boilers to be installed at Battersea would have a grate-area of 918 square feet for a rating of 550,000 lb. per hour, equivalent to 600 lb. per hour per square foot. The latter boiler would be the largest stoker-fired boiler yet installed. In such large boilers in America a new feature had been introduced called "zone air-control," the air being supplied to the fuel-bed through tuyeres which could be controlled individually, resulting in reduced maintenance-costs.

Another new feature of the Fulham station was the use of superheat-control. With the modern tendency for still higher pressures and particularly for higher temperatures, the necessity for that became apparent

*** This and the following contribution were submitted in writing.—SEC. INST. C.E.

when it was realized that the creep-strength of most materials used for superheaters was lowered considerably by an increase of temperature. Thus, for instance, if the temperature were raised from 930° F. to 966° F. the creep-strength of ½-per-cent. molybdenum steel would be reduced to about one-third. In his experience the control of temperature to such narrow limits when the load varied rapidly (a condition which probably did not arise at Fulham) might prove a difficult problem on account of the time-lag that occurred between an adjustment and the resulting change in temperature after the final superheater, which was liable to cause hunting. It would be interesting to have some particulars of the accuracy of control actually achieved.

The use of de-aerators to maintain a low oxygen-content in the boiler-feed was another departure. De-aerators had been in common use in America for many years, and about 10 years ago they had been universal. During a visit to the United States 2 years ago, however, he had observed that in some of the latest installations, as at Milwaukee and Conner's Creek, de-aerators had been omitted without apparent ill-effects, satisfactory de-aeration being obtained within the condensers. In some well-known stations in Great Britain, exceptionally low oxygen-contents were obtained under normal operation without de-aerators. In the past there had been some tendency to exaggerate the complication introduced by de-aerators, and the Fulham plant certainly did not justify such criticism, apart from the additional space occupied by the plant. Nevertheless, station-engineers would certainly be interested to hear from the Authors the actual benefits obtained, particularly under starting conditions.

Another special feature was the use of what might be termed the split feed-pump, the first section being operated, in the case of Fulham, at constant speed, and the second at variable speed, thus avoiding excess pressures in the boiler feed-main at light loads; as the pressure feed-heaters were placed between the two pumps they did not need to be designed for the full boiler-pressures. That system had not been adopted more generally on account of the additional complication introduced and, in America particularly, of the difficulties which had been experienced in the operation of the final boiler feed-pump under variable-load conditions when the temperature of the feed-water to the pumps might vary to a great extent. Further information with regard to the operation at Fulham would be appreciated.

It was to be noted that the circulating pumps were driven by variable-speed motors, a feature which was common in America on account of the widely-varying water-temperatures obtained there and the inability of the turbines to utilize efficiently the very high vacua possible with the very low cooling-water temperatures seasonally obtained there. It would be interesting to hear from the Authors whether advantage was taken of that feature in operation.

Mr. N. G. Gedye observed that it was difficult to understand important

parts of Mr. Hay's Paper in the absence of adequate drawings of the jetty-structure. He suggested that the Author might supplement the description by the addition of a cross section of the jetty and an elevation of a small part of it. The section might, with advantage, show the levels of high and low water of spring and neap tides.

He would ask the Author why it had been considered necessary to provide such exceptionally heavy timber fenders, each built up of eight 14-inch-square driven piles, for small vessels of about 2,000 tons dead-weight capacity. Such heavy fendering was, Mr. Gedye ventured to suggest, unusual and unnecessary.

In regard to the rubber buffers described on p. 14, he had used somewhat similar buffers 4 years ago in the construction of a timber jetty at Erith in the river Thames. Those buffer-blocks, which were 7 inches in diameter and 6 inches thick, were placed between the fender-piles (comprising two 14-inch by 14-inch timbers bolted together) and the face of the jetty structure. They had so far proved satisfactory and were still in good condition. Vessels of about 6,000 tons dead-weight capacity made use of the jetty, and sometimes in coming alongside compressed the rubber blocks 3 inches or more. The blow of the ship was spread to some extent by a floating timber boom which extended along the entire river-face of the jetty.

Mr. Hay, in reply, noted that certain criticisms had been made regarding the shortness of his Paper; it should be remembered, however, that the Paper had been read and discussed with a second Paper also describing the power-station.

It was suggested that the protective seal at the back of the retaining walls, consisting of interlocking steel sheet-piling and asphalt laid on a brick screen, was excessive. It could well be imagined that the interlocking piling was not everlasting, and further, that the brick and concrete filling in the piles could not be looked upon as being watertight, so that, but for the asphalt seal, moisture would penetrate the concrete and would attack the reinforcement-steel. A further suggestion was that the retaining walls were over-heavy in section; it was admitted that such was the case, but in view of the loads imposed on the walls, any likelihood of deflexion had been guarded against. The west wall, as shown in *Fig. 1* (p. 5), was subject to a building-load, the south wall was also subject to loads, and the east wall, which was 60 feet from the river, had necessarily to be ample in section, as it was conceivable that at some period of its existence it might be subject to the full tidal effect of the river. The north wall was only of a temporary nature.

An interesting point had been raised with regard to the depth of the raft. It was suggested that the finished level of the basement could have been raised, thus avoiding the excavation to ballast-level —12 O.D. and the replacement of the excavated ballast by mass-concrete. A certain basement-level had been given to the Consulting Engineers, and after due

consideration respecting the area and depth of the grillages required, it was found that the foundations of those members were within the clay formation; further, after they had been designed, it was found that the spacing of those grillages was so close that the most economical form of construction was to take the whole raft to clay-level, and to fill in between the special work about the grillages with mass-concrete.

The finished lining of the circulating-water tunnels was not the same throughout the circulating-water system, for reasons which were almost self-apparent. The system was described in the Paper as being designed to circulate 14,500,000 gallons per minute, and it consisted of two 10-foot 6-inch diameter intake-tunnels, one discharge-tunnel 11 feet 6 inches in diameter, and three bellmouth tunnels from 7 feet 6 inches to 11 feet 6 inches in diameter. The respective velocities in those tunnels were $3\frac{1}{2}$ feet per second, 6 feet per second, and $2\frac{1}{2}$ feet per second, and the lining materials were therefore chosen to suit those velocities; a blue brindle wire-cut brick sufficed for the intake tunnel, a higher finish of Accrington (a press-brick) was necessary in the discharge-tunnel, whilst in the bellmouth tunnels concrete with a "Gunite" finish had been adopted, as the cost of lining the belling sections precluded the use of brickwork. Although not mentioned in the Paper, it was assumed that it would be understood that those finished linings would be laid on concrete backing filled into the bosom of the cast-iron rings to the level of the flange-top.

Referring to the criticism regarding the absence of adequate drawings of the jetty, he thought that perhaps the Paper was at fault on that point; a very fair description had, however, been given of the type of construction (namely, caissons, piers and reinforced-concrete superstructure), and it was hoped that *Fig. 23* (facing p. 66) would suffice. The fenders, each consisting of a cluster of eight 14-inch by 14-inch Douglas fir timbers, had been thought to be over-large. That point had been carefully considered by the engineers at the time of the design, but experience had shown that smaller fenders were naturally more subject to wear and breakage and that their renewal was troublesome and costly, whilst a larger section increased the buffer-effect by its own resistance to bending. It was interesting to know, from the records given of buffers of a similar character, that they were efficient and stood up to long service.

Messrs. Parker and Clarke, in reply, considered it best to deal with the various points raised under a series of headings.

Construction.

Mr. Dean mentioned (p. 77) that if the works were reasonably fully planned before commencement it should be possible to construct a station, even as large as Fulham, in from 21 to 24 months. The Authors would themselves like to feel that such a station could be constructed and put into operation in so short a period. Their own experience, however, had shown them that, no matter how carefully a complete power-station

was planned, and providing that the engineers were honest in reviewing pre-conceived plans as the work progressed, there were bound to be points which could only be decided as the work proceeded. For example, whilst plans could be prepared, runs forecast, and positions pre-determined for the auxiliary wiring and auxiliary control-gear, the fact remained that in reviewing those plans as the work progressed alterations would of necessity suggest themselves. Apart from that, however, Mr. Dean's hope of 21 to 24 months was not practicable, as only recently the Authors' investigations into deliveries had shown that 33 months were required for the complete delivery of heavy forgings alone, after which at least 9 months' constructional work had to follow before the plant was complete. In their opinion, Mr. Dean would have been nearer the mark if he had suggested a period of 36 to 42 months.

Mr. Dean also referred to the question of wind loading and the general steel construction of the building, and Mr. Matthews mentioned the tonnage of steelwork used. In that connexion, it might be said that the buildings generally had been designed to resist wind loading as called for and in a manner agreed by the London County Council. It should be noted that the building as designed was not a finally completed structure, as space was allotted for future plant and provision was also made for a further extension of the buildings. For that reason, on the north and east sides of the building there was no continuity of floors to the outer walls for the full height of 140 feet. Further, the individual plant structures, such as boilers, were isolated units and were not connected to the main building-frame except by small gangway-supports.

With regard to Mr. Dean's remarks on turbo-generator foundations, the Authors agreed that the adequacy of the curing would always, in a large mass, be somewhat problematical. In the case of the blocks at Fulham, steel reinforcement had been placed around all apertures and on all faces with a view to overcoming shrinkage as far as possible, and up to the present there were no signs of shrinkage-cracks in the blocks. The question whether the mass or framed-structure type of foundation was the better was one that could not be answered in the reply, since such points as synchronous vibration and distribution of load had to be fully considered. It should be borne in mind that Mr. Dean's statements on the subject were based on very recent experience, and it had yet to be proved that his theory would work out satisfactorily in practice. Apart from that, however, on the particular plant to which he made reference, it was the Authors' opinion that the essential reason for the adoption of that type of foundation had been that no other type would have left adequate space for the whole of the auxiliary gear that had to be accommodated below the high-pressure end of the set; it would be interesting to know why the system had not been extended to the alternator end of the set.

Mr. Dean's reference to vibration of induced-draught fans was, they thought, the result of a misunderstanding on his part. The vibration

experienced in the earlier stages with those fans at Fulham had been vibration of the fan-runners, without any excessive steelwork vibration accompanying it. The design of the supporting steelwork at Fulham in relation to the critical speed of all plant had been very carefully taken into account.

Chimneys.

Mr. Dean asked for particulars of the protection afforded to the chimneys. The inside of the chimneys had been lined with a protective paint known as "Keragel," which had been applied over a sealing medium applied direct to the concrete. The measure of protection achieved had been very satisfactory.

Air-Raid Precautions.

The sum of £50,000 shown for air-raid precautions in the make-up of the total cost of the station, whilst allowed for, had not yet been spent. It could, however, be said that that sum of money would only allow for essential services, such as wire protection to all windows, outside sand-bagging of doorways and windows up to a height of approximately 10 feet, and the provision of gas-proof chambers, first-aid stations and shelters inside and outside the station.

Boilers.

The President had referred to the widely-varying characteristics of the coal used, and asked that the average cost of coal fed to the bunkers should be stated. That cost was 7·25*d.* per million B.Th.U.

Apparently Mr. Dodds had been under some misconception regarding the Authors' statement (p. 19) of the limitation on coals that could be used, as he appeared to feel that the limitation referred to the stoker, as represented within the confines of the boiler itself. The Authors, however, had carefully stated that "The type of coal used is controlled in the main by the requirements of the stokers and conveyors." An analysis of that statement should indicate that the Authors were concerned with the quality of the coal from the time that it was brought alongside in the colliers to the time that it was delivered on to the grate, and that any factors in that chain which in any way put a restriction on the coal prevented the market from being kept as wide as would otherwise be possible. The Authors were, in fact, referring primarily to the ease of flow of the coal and were indicating that present conveyor and stoker-hopper designs placed definite limitations on the sizing and moisture-content. They were endeavouring to point out to manufacturers the desirability of paying considerable attention to those points, not only to encourage the better design of conveyors and chutes, but also to lead stoker-manufacturers to pay earnest attention to their hopper designs in order to enable coals of much smaller sizing and higher moisture-content to be used than at

present. The comments by the Authors in that direction were not intended in any way as a criticism, as, in view of the state of the art at the time of installation of the Fulham plant, they considered that that plant had achieved all that it was called upon to do, but naturally they hoped that by passing on their experience still greater progress could be expected in the future.

It was interesting to note the figures given by Mr. Baumann on stoker ratings in the United States and in the new plant to be installed at Battersea as compared with those at Fulham. Those figures raised a point of considerable interest, because it was the Authors' opinion that experience over recent years with the Grid system and base-load stations had shown that the boiler-capacity available in stations, as designed in the past, had not proved to be adequate to ensure full availability of the turbine plant. Boiler-makers had quoted boiler-performance in terms of "maximum continuous rating"; the Authors believed that to be an erroneous term, as it indicated that the figure given could be maintained for a reasonable life of the boiler, whereas experience showed that there was a decline in the evaporative capacity of a boiler over its life, and, further, that if a boiler were forced to work at the rating designated by the manufacturers, efficiency would be sacrificed and maintenance and outage would become excessive. The Authors believed, therefore, that boiler-performance should be expressed in terms of "economic continuous rating," and their experience showed that the figure for economic continuous rating was approximately 85 per cent. of the maximum continuous rating. They had been interested to note Mr. Baumann's comments elsewhere [1] on a recent tour of America, where there was a tendency to develop the practice of providing one boiler to one turbine; in order that that might be practicable it was noted that exceptionally large furnace-volumes had been utilized, giving a heat-release of only 15,000 B.Th.U. per cubic foot per hour, as against the more normal figure associated with British practice of 25,000 B.Th.U. per cubic foot per hour. That seemed to confirm the experience obtained in Great Britain with base-load stations.

The new feature at Fulham of the use of superheat-control was referred to by Mr. Baumann, who asked for information on the accuracy of that control, and referred to the problem of controlling the temperature between narrow limits when the load varied rapidly, which, he agreed, might not be the case at Fulham. On p. 24 it was stated that the final steam-temperature from the boilers was designed to be within $\pm 20°$ F. of the normal temperature of 850° F. at all loads between 150,000 and 260,000 lbs. per hour evaporation. It might be mentioned that the basic figure of 850° F. was capable of adjustment, so that the temperatures of steam from all boilers were equal when measured at the receivers, and the control was completely effective in maintaining the temperature of individual

[1] H. C. Lamb and K. Baumann, "Present-day Trends in Power-Station Practice." Incorporated Municipal Electrical Association; Convention, May 1938.

boilers within the tolerance of $\pm$ 20° F. An important factor was that, owing to the ring connexion at the receivers, there was an interchange of steam between receivers, which normally resulted in the variation in the temperature at any turbine stop-valve being even lower, of the order of $\pm$ 10° F. The importance of that could be appreciated with turbines fitted with two separate admission-groups, in that the temperature-difference between the two groups was seldom more than 10° F. A further point, which was perhaps worthy of remark, was that experience had shown that, with automatic control of temperature, constant superheat could be maintained over the whole life of the boiler.

Mr. Baumann had mentioned the departure in the use of de-aerators to maintain a low oxygen-content in the boiler-feed, and the fact that recent plants in the United States had omitted de-aerator equipment, apparently without any ill-effect, and had asked what results were obtained at Fulham, particularly under starting conditions. At Fulham the de-aerators were actually taken out of service during the starting period, as otherwise the whole system would be under vacuum conditions and the period of starting-up would be unduly prolonged, which would undoubtedly have its effect on the smooth running-up of the machine. That problem, therefore, did not arise. The installation of de-aerators at Fulham had been decided upon for two reasons. Firstly, it effected some simplification in the feed-system. Secondly, the de-aerators themselves constituted a stage in feed-heating, and therefore they obviated an increase in the feed-heating surface that would otherwise have been necessary in order to obtain the final feed-temperature. Another point that had been considered of great importance was the maintenance of the oxygen-content at the lowest possible figure, and in actual practice it had been found that the gases in the feed-water could be reduced to and maintained at a figure of approximately 0·005 cubic centimetre per litre or less. No difficulties had been experienced with de-aerators at either steady or varying loads, as it would be appreciated that the inlet-water to each de-aerator was controlled by a Larner-Johnson valve and the rate of flow through the valve was governed only by the water-level in the de-aerator. It was the Authors' opinion that de-aerators should be looked upon in their dual capacity of de-aeration and feed-heating, and from that standpoint their installation was beneficial.

Mr. Baumann also referred to the split feed-pump system. The most important point in that regard was the absence of any surge-connexions between the lift-pump discharge and the high-pressure feed-pump suction, owing to the designed pressure at that point being 250 lb. per square inch. At the same time, it had been thought advisable when the station was being designed—perhaps the same consideration still applied—not to subject the feed-heaters to full feed-range pressure and temperature. That in itself necessitated a split system. No operating difficulties had been experienced, and there was no surging between pumps. In effect,

the arrangement was very flexible, and it was quite economical in power-consumption. It might be pointed out that the system was a "common bus" system on the discharge side of the pumps, from which it would be immediately realized that the number of pumps that had to be running depended only upon the load on the station, and not upon the number of sets in operation.

Circulating-Water Pumps.

Information had been asked with regard to the operation and advantages of variable-speed circulating-water pumps; in that connexion Mr. Baumann had referred to the widely-varying water-temperatures experienced in America. At Fulham the same wide variation in water-temperature was experienced, the temperature varying between 40° F. and 80° F. The advantage of variable-speed pumps was, therefore, obvious, and it had been found that considerable economies could be effected by running at reduced speeds during certain periods, when a vacuum of 29 inches could be maintained at low speeds on the pumps.

Sulphur-Extraction Plant.

In discussing the sulphur-extraction plant, Mr. Rider and Mr. Damon had mentioned the disposal of the effluent. In that connexion, all that the Authors could say was that it was a problem of which they were aware and on which they hoped to contribute very much fuller information at a not-too-far-distant date.

Both Mr. Kennedy and Mr. Johnstone Wright had referred very strongly to the cost of sulphur-extraction and had expressed hopes that better and cheaper methods would be developed, and that the liability of extracting sulphur from gases would be spread more evenly over other industries than it had been in the past. The Authors had spent a very considerable time on the former problem, and, although Mr. Ulander expressed the opinion that gas-washing plant would be more costly in the future, they felt from their experience that there was reason to hope that future modifications and a different conception of the problem would produce gas-washing plant which would be considerably lower in capital cost and running cost than existing types. The Paper indicated that a sulphur-extraction efficiency of 99 per cent. had been achieved at Fulham. In that figure alone there was left a margin on which considerable modifications could be made, which would have the effect of reducing capital cost considerably, reducing maintenance, and yet, at the same time, maintaining figures within the requirements of the Ministry of Health. Further, it should be realized that the method of treating the effluent was still in its very early stages, and a considerable improvement in that respect could be expected. Contemplation of entirely different methods of extracting the sulphur from flue-gases was limited by the fact that the gases leaving the boilers contained roughly only ½ grain of sulphur dioxide

per cubic foot. If the concentration were considerably higher, fresh methods would be available for tackling the problem. It had to be recognized that recirculating methods were essentially more costly than methods which permitted the discharge of the effluent into a river, but the solution of that particular problem did not lie in the hands of the electrical industry, but in the hands of health authorities and river authorities.

Mr. Kennedy had suggested that electrostatic precipitators might be installed before the gas-washing plant to reduce the amount of material to be dealt with, but it should be noted that the size of the gas-washing plant was determined by the quantity of sulphur to be removed, quite apart from the solid-content in the flue gases.

Dr. Lessing referred to the unit system adopted at Fulham, and to the sub-dividing of units in order that boilers might be run at half load. The Authors were in entire agreement with him that unit construction was definitely an asset in maintaining availability of the plant; whilst the washers were divided in half on each boiler-unit at Fulham, it was not possible under the present arrangement to clean one-half of a washer at a time. However, that was a point which should undoubtedly be borne in mind in any future construction.

In view of Mr. Ulander's suggestion that faint praise had been given to the gas-washing plant, but that pointed criticism had been definitely intended, the Authors had again reviewed that section of their Paper, but they had been unable to find justification for that suggestion. In case there might be any misconception, they wished to state that the Paper had been intended to convey that the gas-washing plant as installed had exceeded expectations in its performance, but that, as would be expected in any new design, there were points in design and operation that needed revision. The principle of the plant and its general construction, however, had proved itself, and the Authors were satisfied that when the modifications referred to had been made the plant would prove entirely satisfactory from the points of view of efficiency, availability, operation and reasonable maintenance-costs.

Thermal Efficiency.

Mr. Johnstone Wright's data regarding the thermal efficiency of base-load stations, both in Great Britain and America, were extremely interesting. They definitely indicated the trend of thermal efficiencies, and the higher figures shown, such as those for Port Washington, indicated the thermal efficiencies that could be achieved by the use of higher pressures and temperatures in combination with re-heating. In the Authors' opinion, there was no doubt that in time to come higher pressures and higher temperatures would be justified, and the question of re-heating would then have to have very serious consideration. The results given by Mr. Wright, however, referred to one aspect of the problem only, namely, thermal efficiency. The Authors, as engineers responsible for producing

a unit of electricity at the lowest possible cost, felt that at the present juncture there was not sufficient evidence available to show an overwhelming argument for the installation of extra-high pressures and temperatures, and in that connexion, it might be appropriate to refer to the curve produced by Mr. Kennedy regarding the cost of efficiency. Considering Mr. Kennedy's and Mr. Johnstone Wright's data together, it would be evident that in any given set of circumstances there were many factors that were bound to affect a decision on the plant to be installed at any one station. Mr. Kennedy's curve indicated that there was a definite value to the extra cost per kilowatt of plant installed to be fixed for any increase in thermal efficiency. That, the Authors agreed, was true, when making comparisons under identical conditions, but they suggested that such identical conditions very rarely applied and that such items as reduced cost of transmission very often more than compensated for extra original capital cost of the station, and thus justified a higher capital cost. On Mr. Johnstone Wright's data, they felt that it remained to be proved that availability and maintenance-costs were low enough at stations of higher thermal efficiency to leave some margin of advantage. In fact, it was interesting to note that, as far as could be ascertained, at Port Washington costs of repairs and maintenance amounted to 0·0126*d.* per unit sent out, which was nearly double the corresponding figure for Fulham, namely, 0·00725*d.* It was also interesting to note, as far as figures could be ascertained, that the cost of production at Port Washington was 0·11685*d.* per unit; if the cost of gas-washing alone were deducted from the cost of production at Fulham, then Fulham's figure became 0·1251*d.* per unit, and in considering those figures it should be remembered that the figures given for Fulham had been obtained in the early stages of working and that very considerable improvements in thermal efficiency could yet be effected.

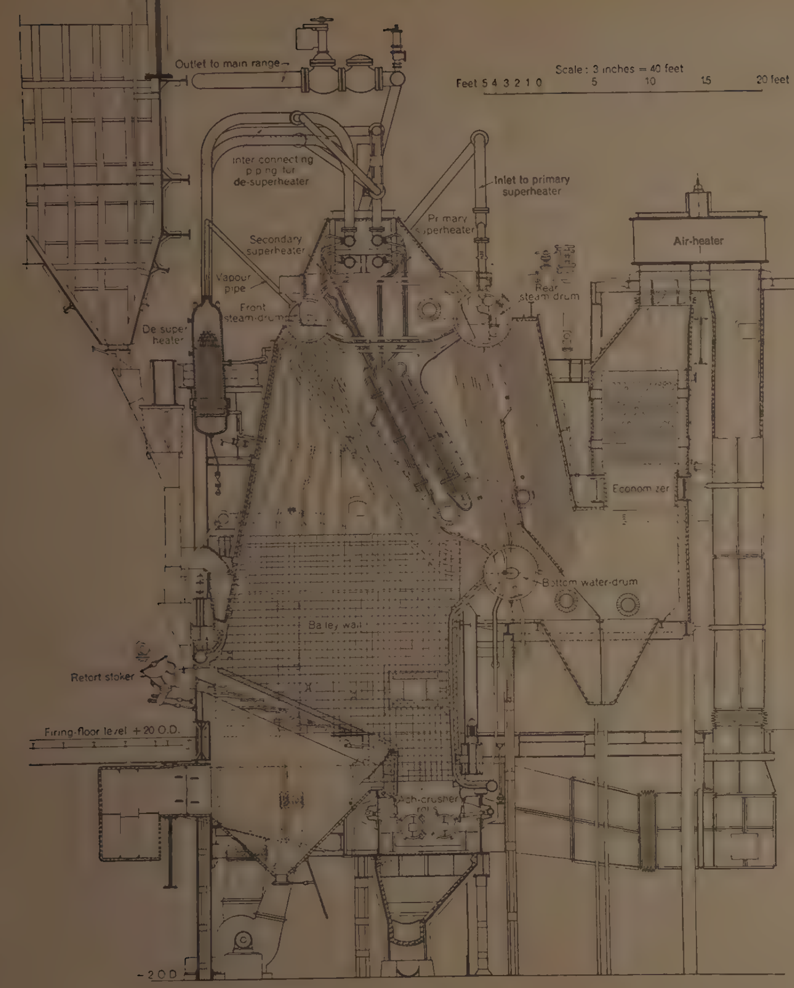
Fire-Fighting.

The Authors were in entire agreement with Mr. Kennedy's comment that it was essential to cut off the current from the section affected by a fire at the earliest possible moment, and under all circumstances where that was possible such a step should be taken before attempting to fight the fire. They did, however, intend to convey that where circumstances arose where supplies could not be cut off, as might be the case under certain emergencies, then it was possible to carry out fire-fighting by the method described with gear alive. Tests in that direction were in the course of being carried out at Fulham, in conjunction with the Electrical Research Association, and it might be possible to give further information on the subject at a later date.

*** The Correspondence on the foregoing Papers will be published in the Institution Journal for October, 1938.—SEC. INST. C.E.

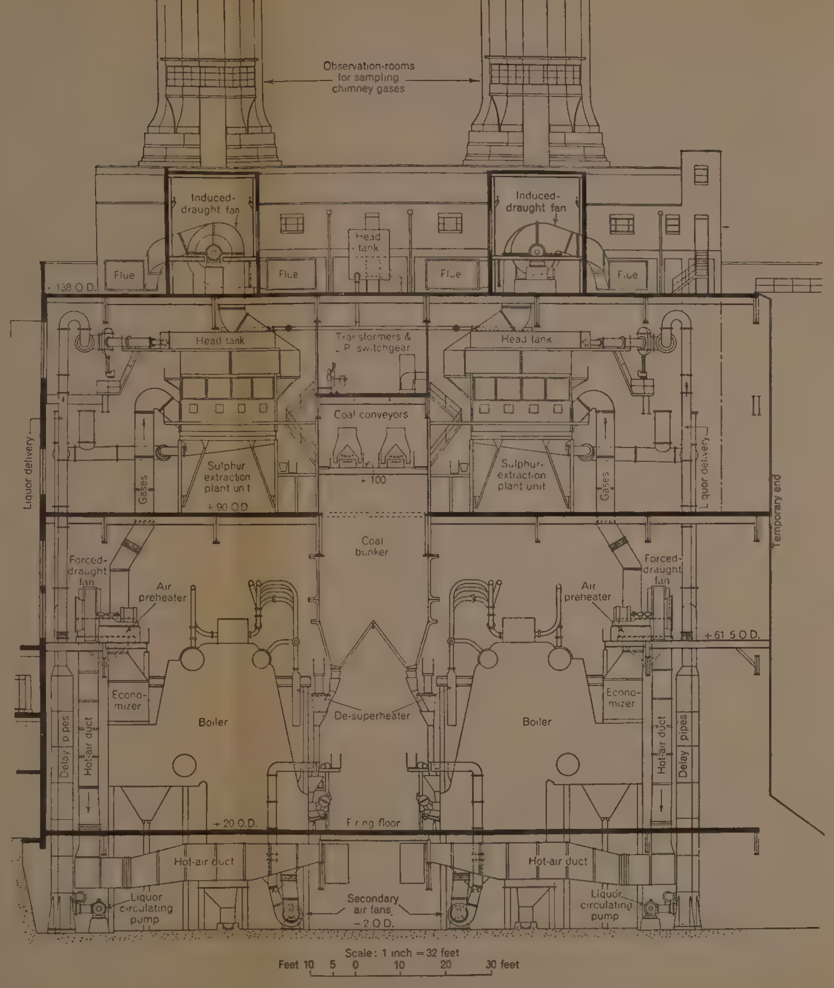
FULHAM BASE-LOAD POWER-STATION: MECHANICAL AND ELECTRICAL CONSIDERATIONS.

Fig: 8.



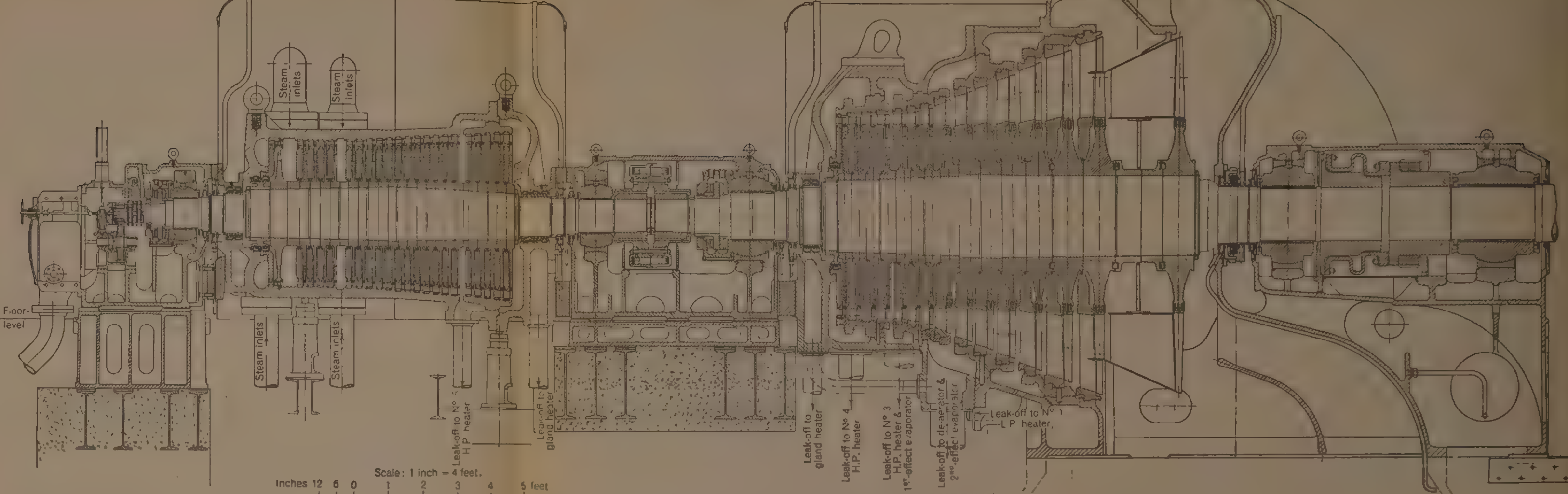
TYPICAL BOILER UNIT: EVAPORATION 260,000 LB. PER HOUR.

Fig: 12.



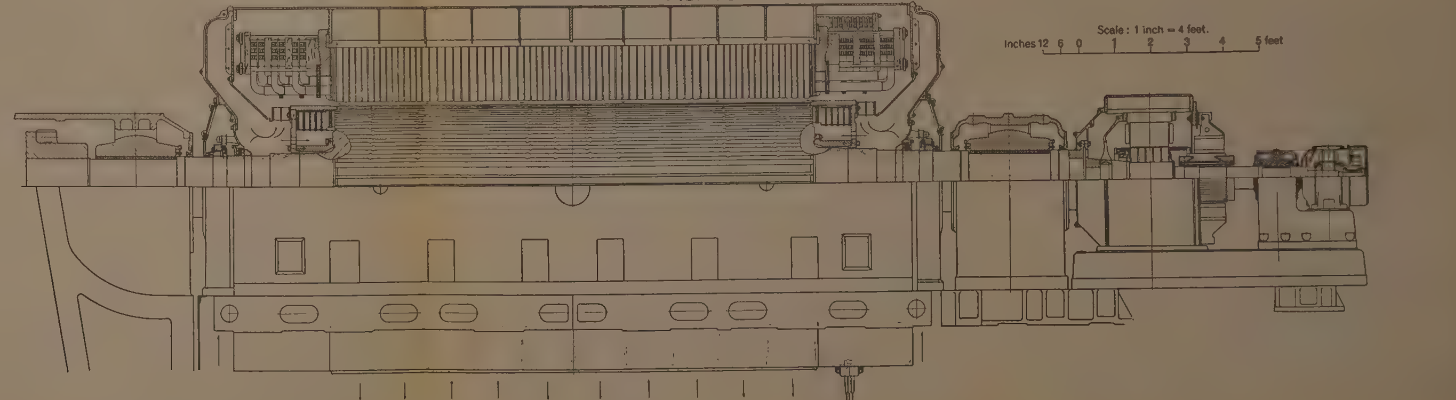
ARRANGEMENT OF BOILERS AND SULPHUR-EXTRACTION PLANT

Fig: 13.



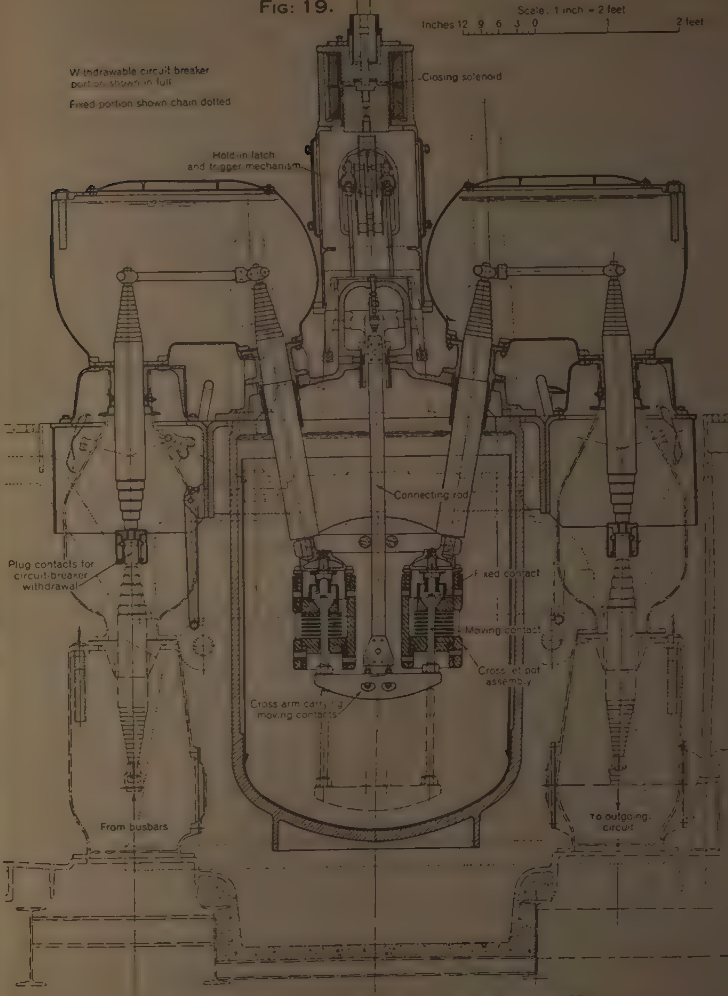
SECTIONAL ARRANGEMENT OF TANDEM TURBINE.

Fig: 15.



SECTION THROUGH 75,000-K.V.A. ALTERNATOR.

Fig: 19.



CROSS SECTION OF 66-KILOVOLT CIRCUIT-BREAKER.

W. C. PARKER and HUBERT CLARKE

William Clowes & Sons, Limited: London.

ORDINARY MEETING.

29 March, 1938.

Mr. SYDNEY BRYAN DONKIN, President,
in the Chair.

The following Paper was submitted for discussion, and, on the motion of the President, the thanks of The Institution were accorded to the Authors.

Paper No. 5154.

"The Reconstruction of Main Road Bridges, Calcutta." †

By MALCOLM RAMSAY ATKINS, C.B.E., B.Sc.(Eng.), and DOUGLAS HENRY REMFRY, B.Eng., MM. Inst. C.E.

TABLE OF CONTENTS.

PART I.—GENERAL DESCRIPTION OF OPERATIONS.*

PROGRAMME OF RECONSTRUCTION.

THE replacement, in reinforced concrete, of seven of the old girder bridges over the two waterways known as the Circular Canal and Tolly's Nullah which form the boundaries of central Calcutta on the north, east, and south,

† Correspondence on this Paper can be accepted until the 1st September, 1938.—SEC. INST. C.E.

* By Mr. M. R. Atkins.

has been carried out in a continuous series of operations since the year 1920, when the Author was appointed Chief Engineer to the Calcutta Improvement Trust. The old bridges, which were narrow and entirely unsuited to modern requirements, formed a serious obstruction to traffic, and in some cases were in imminent danger of collapse. The Public Works Department (Irrigation) of the Government of Bengal had rebuilt one of the most important of them, the Kidderpore bridge over Tolly's Nullah, in steel as a matter of urgency immediately after the War, but it was felt that a comprehensive programme of reconstruction was required for the remaining bridges, and the Calcutta Improvement Trust was eventually authorized to carry out the work with funds contributed jointly by the Government of Bengal, the Calcutta Corporation, and the Trust.

Arch Bridges over the Circular Canal.

Work on the Dum Dum bridge, the first to be dealt with under this arrangement, was commenced in 1923, and completed in 1925. The superstructure of the old lattice-girder bridge, which had a span of 100 feet and a width between girders of 22 feet, was skidded bodily to one side to clear the site for the new bridge, and was kept in use as a temporary bridge for tramway and foot traffic during the period of reconstruction. The skidding operation was carried out successfully with only a few hours' interruption of the traffic. The skidways consisted of two sets of four steel joists supported at one end on the brickwork of the old abutments and at the other on temporary abutments consisting of screw piles with 5-inch diameter shafts suitably braced. Short girder spans connecting the temporary screw-pile abutments with the canal-banks were completed in all details, with temporary approaches, before traffic was interrupted on the old bridge. When all the arrangements were complete the road-metal was removed from the old bridge in order to lighten it, a 25-ton jack was inserted under each of its four corners, and the bridge was lifted clear of its bearings and lowered upon short lengths of steel joists laid on the masonry of the old abutments and forming extensions of the skidways already in position. Hand winches were utilized to haul the bridge into its new position, an operation which required more care than force, when once the bridge had made its first jerk forward. The Manicktola, Beliaghatta and Narkeldanga bridges, of similar type, were also shifted in the same way, except that in the case of the Manicktola bridge the contractors made use of trollies with flanged wheels running on rails bolted to the upper flanges of the traversing girders instead of adopting the simpler expedient of skidding. The use of trollies obviated any risk of the bridge getting out of control and deviating from the correct line during traversing, but had the disadvantage of requiring it to be jacked up and lowered nearly 2 feet, which caused considerable loss of time. The Beliaghatta bridge was a composite structure with cast-iron compression-members and wrought-iron tension-

members connected to the booms by pin-joints. The moving of this bridge caused some anxiety, as it was feared that a sudden jolt might fracture the cast-iron end verticals and cross girders, which were rigidly bolted together. Fortunately the operation proceeded without serious mishap, although an excess of enthusiasm on the part of one of the winch-crews at a critical moment caused a local fracture of a flange of one of the end verticals at the point where the hauling tackle was attached.

In each case special precautions were taken to safeguard the structure of the old bridge before shifting by duplicating any badly-corroded tension-members and by providing additional overhead bracing between the upper booms. All four of the bridges which were shifted in this way for use as temporary bridges were in such a bad state of repair that it was thought prudent to restrict the traffic they would have to carry in their new positions. This restriction was effected in the case of the Dum Dum bridge, which in its original state carried a single tram-track on one side of the roadway, by re-aligning the tram-track along the centre of the bridge with a railed-off gangway for pedestrians on each side. Ordinary vehicular traffic was excluded, there being another bridge within ½ mile to which it could be diverted. The roadways of the other three bridges, each of which had been carrying two lines of vehicular traffic, were restricted in width, by railing off a footpath along one side, to allow of one line of traffic only.

Water-mains, gas-mains, and electric cables carried by the old bridges were relaid on the temporary bridges or on specially-constructed wire-rope suspension-gangways. During the change-over from the old bridges to the temporary bridges and from the temporary bridges to the new bridges pedestrian traffic was accommodated on light pontoon bridges with opening spans.

The four bridges above mentioned were replaced by reinforced-concrete three-hinged arches of 128 feet span, with a 37-foot roadway and two 10-foot footpaths (Figs. 1, 2, 3, 4, and 5, Plate 1). The arch type of construction was adopted after considerable discussion, partly because it provided an open roadway without obstruction of any kind and partly because it was thought to be more satisfying in appearance than any other type. Had the bowstring type, which was adopted for the three later bridges, been better known when these four bridges were designed (1920–23) it is possible that it would have found preference over the arch type, on account of its being better adapted for a subsoil of a yielding nature. As it was, the horizontal thrust of the arch had to be provided for by sloping the foundations of the abutments, providing a vertical thrust-surface at the back of each abutment, and inclining the majority of the piles. These precautions have been successful in preventing horizontal movement of the abutments, in spite of the fact that vertical settlements ranging from a fraction of an inch to 5 inches have taken place.

Different methods of piling were adopted in accordance with the experience obtained as the work proceeded. At the commencement it was

thought that sufficiently good results would be achieved by enclosing each foundation within a ring of interlocking steel sheet-piling and driving piles of the comparatively short length of 25 feet within this restricted area so as to compact the subsoil into a more or less solid mass. This method was adopted at the Dum Dum bridge, but the driving and joining-up of the interlocking sheet-piling proved far more difficult than was anticipated, owing to the unexpected depth of the masonry foundations of the old bridge, which had to be cut through, mostly by hand labour, to a depth of about 20 feet below water-level. When the circuits were finally completed and the reinforced-concrete piles driven it was found that the consolidation obtained was not sufficient to justify the repetition of this method at the other bridges. Accordingly at the Manicktola bridge, after two test-piles had been driven, it was decided to omit the steel sheet-piling, to increase the total number of bearing piles under each abutment from seventy to one hundred and ten, and to increase their maximum length from 25 feet to 45 feet. The piles were pre-cast, and were driven successfully in spite of the difficulty of moulding and handling such long piles in the restricted space available on the canal banks, with the temporary bridge in close proximity. A similar method was adopted at the Beliaghatta bridge, but here the subsoil was found to be so poor that the number of piles under each abutment had to be increased to one hundred and thirty-seven. At the Narkeldanga bridge cast-in-situ piling of the "Vibro" type was adopted, with satisfactory results. In both methods the driving of the battered piles, some of which were at an angle of 23 degrees to the vertical, was less troublesome than was expected.

The foundation-rafts of these four arch bridges consist of continuous slabs of reinforced concrete, partly horizontal and partly sloped at right angles to the piles. The inner edge of each raft is extended 10 feet under the canal towpath to give increased bearing surface, and the outer edge is provided with a vertical thrust-surface, as already stated, which forms a distinctive feature of the design.

In order to allow for boat traffic it was necessary to leave a gap of 42 feet in the centering supporting the arch-ribs during erection. As there was not sufficient headroom to allow of this gap being bridged by girders under the arch-ribs, it was decided to suspend the central portion of each of the seven ribs between a pair of trusses, the ends of which rested on timber staging supported on piles driven in the bed of the canal. At the Dum Dum bridge these were 12-inch-square timber piles of the "cradle" type, and the trusses were also of timber. As these timber trusses were clumsy to handle, and gave a greater deflexion than was desirable, the contractors for the other three bridges across the Circular Canal made use of steel trusses and supported their staging on steel screw-piles. The facts that three of the bridges were skew bridges, that the number of trusses available was limited, and that it was necessary to defer the concreting of the lateral bracing between the ribs until all the ribs had

taken their initial settlement, led to many complications at this stage of the work, and required much patience and scheming on the part of the erecting staff.

The arch-ribs themselves are of rectangular section, with a depth of 2 feet 9 inches at the crown, increasing to 4 feet at a point midway between the crown and the springings. The hinges are of cast iron with 3¼-inch diameter pins of axle steel. The main reinforcement of the arch-ribs consists of 1⅝-inch rods, the ends of which are screwed and secured to the flanges of the hinges by nuts on each side. Joints are provided in the superstructure and deck-slab over each of the three hinges. The roadway of the Dum Dum bridge was paved with asphaltic concrete, but this paving was found unsatisfactory, and the roadways of all subsequent bridges have been paved with compressed asphalt blocks, 2 inches thick, laid on a bed of cement mortar. These blocks have withstood with fair success the wear of the heavy iron-tired bullock-cart traffic, which is still common in Calcutta, and appear to be very little affected by changes of temperature.

Water-mains, gas-mains, and electric cables were laid under the footpaths. In the case of the Manicktola bridge this necessitated the raising of the footpaths to a height of about 2 feet above the roadway, as the mains to be accommodated included one 36 inches in diameter.

Alipore Bridge.

The fifth bridge which the Trust was called upon to replace was a plate-girder bridge of three spans crossing Tolly's Nullah at Alipore. The total length of the old bridge was 195 feet, but it was found possible to reduce this to a single span of 150 feet. One of the side spans of the old bridge had collapsed shortly before the Trust was asked to undertake the reconstruction, and the first stage of the operations included the removal of the debris of the collapsed span and the erection of a temporary bridge to carry foot traffic and a 24-inch water-main.

The new bridge (Figs. 8, 9, and 10, Plate 1) is of the bowstring type with a 30-foot roadway between the ribs and two 6-foot footpaths outside them. The footpaths are raised about 5 feet 6 inches above the roadway to provide space for three steel water-mains, one of which is 51 inches in diameter.

The abutments are of brickwork on concrete foundations, under each of which are driven seventy-one reinforced-concrete piles of the "Simplex" type, ranging in length from 15 feet to 27 feet. No settlement of the abutments has been observed, the piles being driven into an underlying layer of fine sand which was not found at the sites of the four arch bridges. The inner face of one of the foundations is protected by a line of steel sheet-piling, as the bridge spans a tidal waterway, and the failure of the old bridge was due to the undermining action of the current. In erecting the superstructure of the new bridge, use was made of one of the screw-

pile piers of the old bridge for carrying a portion of the staging. A waterway of 30 feet which had to be left open for boat traffic was spanned by steel trusses, as in the case of the previous three-hinged arch bridges, but in this instance the head-room available was sufficient to allow the ribs to be carried on the tops of the trusses instead of between them. Each arch-rib was divided into five sections for the purpose of concreting, the two end sections being concreted first, the central section next, and the two intermediate sections last. The ribs are 3 feet 1 inch wide and 5 feet deep at the centre of the span. The tie-beams are of structural steel encased in concrete and bolted to steel-plate anchorages which are embedded in the concrete at the point of intersection of the ribs with the tie-beam. The hangers are of dumb-bell section with seven 1-inch rods in each flange. Four sets of H-section overhead bracings, each slightly arched in elevation, connect the two arch-ribs. The bridge is supported on cast-iron hinged bearings, one of which is fixed and the other carried on rollers. The concreting of the tie-beams and hangers was deferred until the cross girders and deck-slab had been completed and the centering struck, so as to allow the steel to become nearly fully stressed before it was encased.

Chitpore Bridge.

The sixth bridge of the series, known as the Chitpore bridge, was in replacement of a lattice-girder bridge crossing a lock on the Circular Canal. The abutments of the old bridge were built on a solid mass of brickwork which had its foundations below the invert of the lock. This brickwork was in such sound condition that it was made use of as a foundation for the new abutments, which consist of two pairs of reinforced-concrete grillages, 8 feet square, keyed into the existing brickwork and connected with each other by reinforced-concrete distributing beams. The new bridge (Figs. 11, 12, and 13, Plate 1) is of the bowstring type with a span of 78 feet and a total width of 87 feet 6 inches, which includes a 38-foot 6-inch central roadway between the ribs, and two 9-foot 3-inch side roadways and two 10-foot footpaths outside the ribs. The ribs are 3 feet wide and increase in depth from 3 feet 3 inches at the centre of the span to 4 feet at the ends.

The overhead bracing takes the form of two transverse members of "H" section, each comprising two vertical flanges 36 inches deep by 9 inches wide connected together by a web 4 inches thick by 7 feet wide which conforms with the curvature of the arch-ribs. The hangers are of dumb-bell section with six $1\frac{1}{8}$-inch rods in each flange. Steel trusses were used for spanning the waterway of the lock during erection. The footpaths of the bridge-approaches are carried on reinforced-concrete cantilevers which project 10 feet from the wing-walls of the abutments and have their inner ends anchored to blocks of concrete.

The bridge has fixed supports at one end and rocker supports at the

other. The rocker supports are simply short square columns of reinforced concrete fitted with convex caps and shoes of cast iron which rest in concave seatings of flatter curvature. A light steel temporary bridge of cantilever type was built alongside the main bridge to carry foot traffic, electric cables, and a 14-inch gas-main during the period of reconstruction.

Tollygunge Bridge.

The seventh and last of the bridges dealt with in this Paper is known as the Tollygunge bridge. The old bridge crossed Tolly's Nullah with three spans of the plate-girder type built as continuous girders, and was in such a dangerous condition through corrosion that it had been closed even to foot traffic before the reconstruction was undertaken. As it was out of the question to make use of the old structure in any way, a new temporary bridge of three spans formed of materials recovered from the approach-spans of the temporary bridges already described was erected a short distance away. The new bridge (*Figs. 14* and *15*, pp. 116 and 117) is of the reinforced-concrete bowstring type, with a span of 110 feet and a road-width of 30 feet. Two 8-foot footpaths are carried outside the ribs on the projecting ends of the main cross girders. The arch-ribs are 2 feet 6 inches wide, with an effective rise of 27 feet 6 inches, and a depth of 3 feet 3 inches at the centre of the span, increasing to 4 feet 7½ inches at the ends. Each tie-beam contains twenty-eight rods 1¼ inch in diameter, ranging in length from 112 feet 6 inches to 122 feet 9 inches, which were imported in single lengths bent double for shipment. The supports are of the fixed and rocker type, the concrete rockers having cast-iron caps and shoe-plates about 3 feet square. The top bracings consist of six transverse beams 2 feet 6 inches deep by 9 inches wide spaced in line with the hangers. These beams have a camber of 9 inches and are all connected together by webs 3½ inches thick pierced by 5-foot 6-inch octagonal openings. The hangers are of dumb-bell section with four 1¼-inch rods in each flange. The abutments and foundations are similar to those of the Alipore bridge, except that the piling is of the "Vibro" type.

Costs.

The total cost of the operations described in this Paper, including the temporary bridges and other incidental works, amounted to approximately £240,000. The new arch bridges cost on an average £28,000 each, the Alipore bridge £15,000, the Chitpore bridge £10,000 and the Tollygunge bridge £8,000. These figures cannot be accepted as giving a true measure of the relative cost of the different types of bridges, as the cost of labour and materials was high when the arch bridges were built, and the cost of the bowstring bridges was reduced by keen competitive tendering.

General Remarks.

The labour employed was entirely Indian. As reinforced-concrete

construction was practically unknown in Bengal when the first bridge was designed, some difficulty was experienced in training the labour in the accurate placing of the reinforcing steel. For this reason progress was very slow in the earlier bridges, but improved greatly as the necessary experience was gained. Great care was taken throughout to ensure that all steel had a sufficient protective covering of concrete, and the fact that no serious defects have come to light indicates that the work was well done. All the cement and most of the steel was of Indian manufacture. The coarse aggregate was crushed "trap" rock which had to be brought 200 miles by rail to Calcutta, there being no stone of any kind in the locality. The fine aggregate was a mixture of crushed quartz and river-sand. All concrete was machine-mixed and was kept protected from the sun by wet "gunny" bags for 3 weeks.

Contractors and Engineering Staff.

The contractors for the Dum Dum bridge were Messrs. Gammon & Sanderson, of Bombay. The Manicktola, Beliaghatta, Narkeldanga, Alipore, and Chitpore bridges were built by the Constructional Department of Messrs. Bird & Co., of Calcutta, whose Departmental Head, Mr. G. F. Walton, M. Inst. C.E., was responsible for the design of the centering and other details, and the Tollygunge bridge by Messrs. Hindustan Engineering and Construction Co., of Calcutta.

Subsidiary contracts were placed as follows:—

Dum Dum temporary bridge	Messrs. Burn & Co.
Manicktola temporary bridge	Messrs. Braithwaite & Co.
Beliaghatta temporary bridge	Messrs. Bird & Co.
Narkeldanga temporary bridge . . .	Messrs. John King & Co.
Foundations and abutments of Alipore bridge.	Messrs. B. B. Chatterjee & Sons, with Messrs. Simplex Piling Co. as sub-contractors.
Foundations and abutments of Tollygunge bridge.	Messrs. J. K. Mitter & Co., with Messrs. John King & Co. as sub-contractors for the "Vibro" piling.

Messrs. John King & Co. also undertook the "Vibro" piling for the Narkeldanga bridge as sub-contractors under Messrs. Bird & Co.

Mr. D. H. Remfry, M. Inst. C.E., prepared the designs of the four arch bridges and of the Tollygunge bridge, and acted as Consulting Engineer to the Trust during the erection of all seven bridges. Dr. M. A. Korni, M.I.E. (Ind.), and Mr. S. K. Ghosh, B.Sc., Assoc. M. Inst. C.E., of Messrs. Bird & Co., were responsible for the original designs for the Alipore and Chitpore bridges, which were accepted after modification by Mr. Remfry.

The works were carried out under the supervision of the regular engineering staff of the Calcutta Improvement Trust, the officers directly responsible under the Author being Mr. J. A. Stewart, M. Inst. C.E., Deputy Chief

Engineer, and Mr. J. N. Das Gupta, B.A., B.E., M.I.E. (Ind.), Senior Assistant Engineer. Mr. S. G. Orr-Ewing, Assoc. M. Inst. C.E., acted as temporary Bridge Engineer during the erection of the Dum Dum bridge.

PART II.—DESIGN OF NEW BRIDGES.*

Loadings.

The Dum Dum, Manicktola, Beliaghatta, Narkeldanga, and Chitpore bridges, which cross the Circular Canal, are all upon either main roads or roads leading outwards to industrial and factory areas which are now developing rapidly. These bridges are designed for the heaviest loadings, approximating very closely to the Ministry of Transport standard loadings. As a rule the deck-loads slightly exceed this standard, as a slow-moving boiler-truck with two 25-ton axles is provided for. In the case of the Chitpore bridge the main arch-ribs and tie-bars were designed to carry a somewhat smaller load, namely, 190 lb. per square foot uniformly-distributed load and 2,200 lb. per foot width of roadway knife-edge load on the three roadways and 60 lb. per square foot on the two footpaths. The decks and hangers were designed for the full Ministry of Transport loading, and could also alternatively carry the 50-ton boiler-truck.

The Alipore bridge and the Tollygunge bridge, across Tolly's Nullah, serve a residential quarter, and were therefore designed for lighter loadings. The roadways and deck-systems of these two bridges were designed to carry a uniformly-distributed live load of 133 lb. per square foot including impact, or, alternatively, heavy lorries having a 12-ton back axle plus 50 per cent. impact. These heavy lorries in the case of the Tollygunge bridge were considered as equivalent to 360 lb. per square foot distributed plus a knife-edge load of 2,200 lb. per foot width of roadway on the roadway deck-slabs and cross girders. The footpaths were designed for a load of 112 lb. per square foot. The arch-ribs and tie-beams were designed for a distributed load of 133 lb. per square foot plus 2,200 lb. per foot width of roadway knife-edge load upon the roadways, and 112 lb. per square foot on the footpaths. This gives a heavier deck and hangers in proportion to the main arch-ribs than would be the case if the standard Ministry of Transport loadings were used.

Working Stresses.

The unit working stresses which have been used have in general progressively increased during the last 13 years as more experience in fabrication has been acquired by the contractors and the labour employed. This

* By Mr. D. H. Remfry.

increase is also partly justified by the improved qualities of the cement now available in India. Roughly, the working stresses in the concrete in the deck-slabs and cross girders have been increased from 600 lb. per square inch at the Dum Dum bridge, built in 1923, to 750 lb. per square inch at the Tollygunge bridge, completed in 1936. The working stresses in the concrete of the arch-ribs have been increased from a maximum of about 765 lb. per square inch at the Dum Dum bridge to a maximum of about 985 lb. per square inch at the Tollygunge bridge.

The working stresses in the hangers, however, have been reduced and are lower in the Tollygunge bridge than in the previous ones.

Arch Bridges.

Main Features of Design.

The four bridges over the Circular Canal are all three-hinged arch bridges (Figs. 1, 2, and 3, Plate 1), three of them being built upon the skew. They all replaced old bridges of cast or wrought iron, and being on the same alignment as the older bridges the abutments were built into, and butted against, old and well-consolidated approach-road banks.

Each bridge consists of seven ribs of 128 feet span between end hinge-pins. The five central ribs are from 3 feet to 3 feet 1½ inch wide and from 2 feet 9 inches to 4 feet or 4 feet 2 inches in depth, spaced at 9-foot centres. The outer ribs, which carry the footpath-loads mainly, are similar, but are only from 2 feet to 2 feet 5½ inches wide, being spaced at about 8-foot centres from the nearest intermediate rib.

The foundations were spread by using a strong raft, the level of which was kept as high as possible so as to rest near to the original upper crust of the soil. The bottom of this raft was sloped for the greater part of its area so as to be practically perpendicular to the resultant thrust thereon. A particularly important part of these foundations is the vertical thrust-surface, 8 feet in height and with its top edge 6 feet above the level of the end hinge-pin, which in all cases butts against the solid approach-road bank. This thrust-surface obviates any lateral movement of the raft, even should considerable vertical settlement take place.

In the Dum Dum, Manicktola, Beliaghatta, and Narkeldanga bridges the piles were driven vertically along the front edge of each raft, and were battered under the main body of, and along the rear edge of, the rafts. With this arrangement the piles generally slope in the direction of the resultant thrust, whilst, in the three later bridges, the area of subsoil over which the points of the piles distribute the resultant thrust is considerably —from 25 to 33 per cent.—greater than the area of the bottom of the raft.

Dum Dum Bridge Foundations.

In this case the area covered by the raft was surrounded by interlocked sheet-piling 20 feet deep. Within this area reinforced-concrete

piles 20 to 25 feet long were driven. The piles near the canal-face of the abutment were driven vertically; but the remaining 70 per cent. of the piles were battered, being driven perpendicularly to the bottom surface of the raft. The skew of this bridge is 72 degrees.

The foundations have settled vertically to the extent of about 5 inches. This was mainly due to the fact that an old foundation of a suspension-bridge of very early date was found below the abutment-site; as the masonry of the older bridge extended about 18 to 20 feet below the level of the bottom of the new Dum Dum bridge raft, the ground was very badly disturbed in removing those portions of the old foundations which obstructed the driving of the piles or sheet-piling.

Manicktola Bridge Foundations.

Two trial piles, one of which was 80 feet long, were driven in order to ascertain if any firm band of material of good supporting power could be found at a reasonable depth. Such a band of hard clay occurs in many parts of Calcutta, but none was found at this site. It was finally decided to use one hundred and ten pre-cast concrete piles of a maximum length of 45 feet under each of the two rafts. This foundation has proved very stable, although, as expected, some slight settlement has taken place.

Beliaghatta Bridge Foundations.

In the case of this bridge the sub-soil proved to be poor. Loading-tests upon 13½-inch-square piles 35 feet long showed that movement might be expected when the superposed load on groups of three piles approached from 24 to 28 tons per pile. As, however, each pile weighed 3 tons, the settlement started under total loads of from 27 to 31 tons per pile. The front edge of each foundation facing the canal was protected by driving interlocking sheet-piling. One hundred and thirty-seven reinforced-concrete piles were used in each abutment.

Resultant Loads on Foundations of Beliaghatta Bridge.

The horizontal thrust from each intermediate arch-rib is as follows:—

Under dead loads	201·8 tons
Under live loads	96·0 ,,
Total	297·8 ,,

The vertical reactions at the abutment are:—

Under dead load	109·5 tons
Under live load, full uniform load, plus knife-edge load at abutment without impact	45·0 ,,
Total	154·5 ,,

The resultant thrust upon the hinge-pin is thus 336 tons.

The weight of the abutment strip having a width of 9 feet opposite to a rib, together with the earth filling, is	421 tons
The live load on the abutment approach per rib may be taken as	21 „
Total	442 „

The resultant loads on the bottom of the raft per 9-foot strip are :—

Vertical load	596·5 tons
Horizontal thrust	297·8 „
Resultant	664 „

The surface area of the 9-foot strip of raft is 49 feet by 9 feet = 441 square feet, and the pressure is thus 1·50 ton per square foot. The resultant thrust passes very close to the centre of the raft.

The pressure under the original approach-road embankment, before the new bridge was constructed, would have been 1·0 ton per square foot. The extra load due to the bridge is, therefore, only ½ ton per square foot. The raft is 90 feet long by 47 feet 6 inches wide in plan, the surface-area measured on the slope being 90 feet by 49 feet. This raft is supported upon one hundred and thirty-seven piles ranging in size from 13½ inches square and 35 feet long to 14½ inches square and 45 feet long. Each arch-rib is supported upon a strip of raft 49 feet by 9 feet, and the carrying power is increased by using eighteen piles to each strip. The soil below the raft appears to be a fairly fine silt which extends for a considerable depth; its angle of internal friction β appears to be about 19 degrees.

The average ultimate carrying-capacity of a 13½-inch-square pile 35 feet long is approximately 29 tons, including the weight of the pile itself. The ultimate carrying capacity of such a pile is made up of (i) its bearing resistance, (ii) its frictional resistance. The bearing resistance may be calculated by the formula :—

$$\sqrt{l} \times A_b \times w\left(\frac{1+\sin\beta}{1-\sin\beta}\right)^2,$$

where l denotes the length of pile in feet.

A_b „ area of bulb of pressure (= 4 times sectional area of pile = 5·04 square feet)

w „ weight of 1 cubic foot of soil (= 110 lb.)

$\beta = 19$ degrees;

whence the bearing resistance $= \sqrt{35} \times 5{\cdot}04 \times \frac{110}{2{,}240}\left(\frac{1{\cdot}326}{0{\cdot}674}\right)^2 = 5{\cdot}7$ tons.

The frictional resistance of the pile may be calculated by the formula :—

$$\mu \times w\frac{l}{2}\left(\frac{1 - \sin\beta}{1 + \sin\beta}\right)l \times A_s,$$

where μ denotes the coefficient of friction ($= \tan\beta = 0{\cdot}344$)
A_s „ surface of pile per foot ($= 4{\cdot}5$ square feet).

Hence the frictional resistance $= 0{\cdot}344 \times \frac{110}{2{,}240} \times \frac{35}{2}\left(\frac{0{\cdot}674}{1{\cdot}326}\right) \times 35 \times 4{\cdot}5$

$= 23{\cdot}6$ tons.

The total ultimate resistance of the pile is thus 29·3 tons. This agrees reasonably with the results of tests.

In the Beliaghatta bridge the piles are driven from the bottom surface of the raft, which may be taken as 12 feet below the average surface-level of the bank of the canal; the average pile, being 14 inches square by 40 feet long, may be assumed to extend from 12 feet below ground to 52 feet below ground. The bearing resistance of the pile may be taken as

$$\sqrt{52} \times 5{\cdot}46 \times \frac{110}{2{,}240}\left(\frac{1{\cdot}326}{0{\cdot}674}\right)^2 = 7{\cdot}5 \text{ tons.}$$

The lateral pressure per square foot on the side of the pile is :—

$$wl\left(\frac{1 - \sin\beta}{1 + \sin\beta}\right) = l \times 0{\cdot}025.$$

This lateral pressure at a point 12 feet below original ground-level is $12 \times 0{\cdot}025 = 0{\cdot}3$ ton per square foot; at 52 feet below original ground-level it is $52 \times 0{\cdot}025 = 1{\cdot}3$ ton per square foot. Hence the average lateral pressure per square foot on a pile 40 feet long is $\frac{1}{2}(0{\cdot}3 + 1{\cdot}3) = 0{\cdot}8$ ton per square foot of surface.

The frictional resistance of the pile is :—

$\mu \times$ average lateral pressure $\times l \times A_s$ (where $l = 40$, $A_s = \frac{14}{12} \times 4$ $= 4{\cdot}66) = 0{\cdot}344 \times 0{\cdot}8 \times 40 \times 4{\cdot}66 = 51{\cdot}4$ tons.

Hence the average ultimate resistance of a pile is 58·9 tons.

The ultimate supporting power of eighteen piles should be 1,060 tons; deducting the weight of the piles themselves, namely 65 tons, their ultimate load-carrying capacity should be 995 tons, giving a factor of safety of $\frac{995}{664} = 1{\cdot}5$.

The above calculation assumes that (i) the whole load is carried by the piles, and (ii) each pile of a group is capable of carrying the load supported by a single pile. Neither of these assumptions is correct unless the piles are

very widely spaced and the raft is supported clear of the subsoil-level. In the Appendix to this Paper (pp. 121 *et seq.*) the carrying power of a group of piles supporting a raft is considered. It is, however, difficult to arrive at definite conclusions. The Author is of opinion that in the Calcutta soil the base of a group of piles carried to a depth of, say, 45 or 55 feet below the surface of the pre-existing ground-level must be capable safely of sustaining a load which exceeds by some reasonable percentage—probably at least 15 to 20 per cent.—the load previously supported at that depth, and that in addition to this the sides of the block of soil below the raft engaged by the group of piles will offer frictional resistance to movement which will materially increase the carrying capacity by transfer of load to the surrounding strata. This frictional support may in the cases of the Beliaghatta, Manicktola, and Narkeldanga bridges increase the carrying-capacity by a further 20 per cent.

General Remarks on Arch Bridges.

In Calcutta it is customary to use loadings of from 0·75 to 1·0 ton per square foot on shallow foundations. With these loads, if the structure is small and the foundations take up a small proportion of the total area of the building site, practically no settlement takes place. Where, however, the building is large and heavy and the foundation-trenches take up a larger proportion of the total site-area, considerable settlements are often observed. The buildings appear to settle slowly during several years. Presumably, as the building settles the soil below compresses and the bulb of pressure below each part of the foundations increases and widens, until finally a stable condition is reached and is maintained for so long as the subsoil-water level is unchanged.

When, however, the structure is of large size and area, so that the whole of the site is covered by the foundation-raft, it is naturally to be supposed that such high loadings as from 0·75 to 1 ton per square foot are not admissible if excessive settlement is to be avoided. It is probable that with a raft approximately 90 feet by 50 feet in size a load of from 1·3 to 1·5 ton per square foot (from 0·3 to 0·5 ton per square foot more than the pressure previously existing at the raft-level) could not have been carried without excessive settlement if piling had not been employed.

The piling not only consolidates the soil below, and transmits the load to a much greater distance below the surface where the increase in pressure per square foot will be much less in proportion to the pre-existing pressure at the point, but it also enables a greater spread of the load to be obtained by the use of battered piles. Finally, it forms a large and compact mass, the sides of which obtain considerable frictional support from the surrounding soil.

In foundations in the alluvial soil of Bengal it is not possible to work to factors of safety such as are usual elsewhere. In buildings in Calcutta

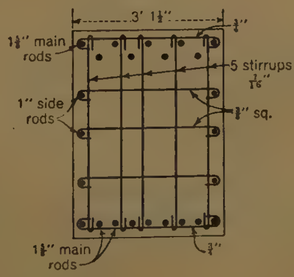
the factor of safety is often unity, and sometimes appears to be less than unity in that settlement continues for some considerable time. In some heavy commercial buildings a settlement of 10 inches has been observed. Even in old buildings which have stood for from 60 to 80 years, further settlements sometimes occur at intervals, chiefly after heavy floods or exceptional drought. In the case of the Canal bridges the conditions are not likely to alter, as the Canal water-level varies very little and the level of the subsoil water is kept constant by the near proximity of the Canal. These foundations all experienced the somewhat severe earthquake of 1933 without showing any extra settlement due thereto.

Three of the Canal bridges are skew bridges, the angle of skew being 72 degrees in the Dum Dum bridge and 75 degrees in the Manicktola and Beliaghatta bridges. The seven arch-ribs forming each bridge are very strongly braced together. In the centres of the span the ribs merge into and are connected by the roadway-slabs; but as the ribs curve downwards, the deck-system above is supported by columns, whilst the ribs themselves are braced together with transverse horizontal struts and diagonal bracings to form a very rigid structure. Between the columns which support the deck-systems strong diagonal sway-bracings are provided. By these means the otherwise somewhat slender ribs, which have hinges at each end and at the centre, are held in line, and an exceptionally rigid structure is produced. The hinges are of cast iron with 3½-inch-diameter hard steel pins. The open joints at the hinges are packed with felt impregnated with bitumen.

Design of Arch-Ribs.

Fig. 6 shows a typical section of an arch-rib and illustrates one of the five intermediate ribs at about the quarter-point of the span. The main longitudinal rods, 1⅝ inch in diameter, are in two layers at the top surface

Fig. 6.



to enable the concrete to be placed more readily. In the bottom of the ribs the main rods are in one layer. The concrete was placed in a slightly wetter condition along the bottom surface until the level of the lower set of longitudinal rods was reached. The main longitudinal rods are held in line and prevented from spreading by heavy horizontal transverse rods

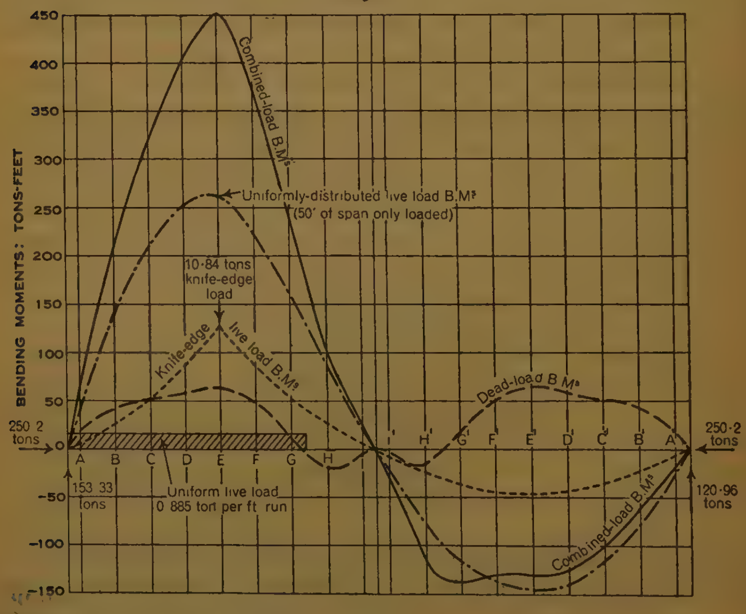
$\frac{3}{4}$ inch in diameter spaced 8 inches apart and hooked over the outer rods. The main longitudinal rods are also connected together across the depth of the rib by sets of five stirrups, the sets being spaced 8 inches apart. In the Dum Dum bridge these stirrups were made of $\frac{1}{2}$-inch diameter rods; they proved, however, to be too stiff and it was found difficult to get them taut, and in subsequent bridges the stirrups were made $\frac{7}{16}$ inch, and finally $\frac{3}{8}$ inch, in diameter. Along each side of each rib three 1-inch diameter longitudinal side rods were used, which were connected together across the width of the rib in pairs by $\frac{3}{8}$-inch square-section stirrups or binders spaced 8 inches apart.

The rib has all its component parts strongly knit together, and the reinforcements are so connected together that the lateral expansion of the concrete under longitudinal shortening of the rib is well resisted. The concrete used is of 1 : 2 : 4 mix; but at the ends of the ribs adjacent to the hinges 1 : $1\frac{1}{2}$: 3 concrete is used. To assist in holding the reinforcements in position in the later bridges, light steel frames were used which remained permanently in the structure.

Bending Moments.

Fig. 7 shows the bending moments for one of the intermediate arch-ribs

Fig. 7.



under the condition of loading which produces the maximum stress at the quarter-point.

The corresponding horizontal thrust was 250 tons.

The stresses produced, calculated by the approximate method, were :—

Direct stress	+ 245 lb. per square inch.
Bending stress	± 520 ,, ,,
Total . . .	+ 765 to — 275 lb. per square inch.

Alipore Bridge.

Design.

This bridge (Figs. 8, 9, and 10, Plate 1) is a bowstring or tied arch of reinforced concrete, 150 feet in span with a rise of 28 feet. The bridge is divided into fifteen 10-foot bays. The two main arch-ribs are spaced at 35-foot centres and carry a 30-foot clear roadway between ribs and two 6-foot wide footpaths cantilevered outside the ribs. A 4-foot 3-inch water-main is carried on one cantilever extension below the footpath, and one 3-foot and one 2-foot main on the other, the footpaths being raised about 5 feet 6 inches above the roadway.

Arch-Ribs.

Each arch-rib is 3 feet 1 inch wide, and 5 feet deep at the centre of the span increasing to 8 feet 1½ inch deep at the ends. The ribs at the centre have twenty-four 1-inch diameter rods in the top surface and twenty-four similar rods in the bottom surface. Transverse horizontal rods ½ inch in diameter spaced at 9-inch centres connect the outer rods of each outer layer. Stirrups ⅜ inch in diameter in sets of six each connect the longitudinal rods across the depth of the rib, the sets being spaced at 9-inch centres. Two longitudinal rods ½ inch in diameter are placed in each side of the arch-rib. Two sets of rectangular-section spiral bindings of ¼ inch diameter at 5 inches pitch reinforce the arch section.

Overhead Bracings.

Four sets of H-section overhead bracings spaced at 20-foot centres connect the main ribs. These bracings have 24-inch by 8-inch flanges connected by webs 6 inches thick and 4 feet 8 inches wide. Each bracing is arched, having a rise of 2 feet. The arching of the overhead bracings, although it does not detract from the appearance of the bridge when viewed down the centre-line, gives the bridge a peculiar and not altogether pleasing appearance when approached diagonally from a distance.

Tie-Beams.

The tie-beams are of structural steel embedded in concrete, each beam consisting of twelve bars 6¼ inches by 1 inch in six pairs. The joints in these tie-bars are staggered and riveted. The ends of the tie-bars are bolted with turned bolts to anchor-plates fitted with thrust-plates and

shoes. The cross girders and hangers are spaced at 10-foot centres. The roadway consists of a slab $9\frac{1}{2}$ inches thick. The bridge is mounted on roller bearings at the expansion-end and on knuckle bearings at the fixed end.

Hangers.

The hangers are of dumb-bell section, with a width of 3 feet at the top increasing to 3 feet 3 inches at the bottom. The flanges are 8 inches wide and the web 3 inches thick. Each flange has seven main rods 1 inch in diameter. The rods in each flange are provided with binders $\frac{3}{16}$ inch in diameter, spaced at $2\frac{1}{2}$-inch centres, whilst $\frac{1}{4}$-inch-diameter stirrups spaced at 5-inch centres connect the flanges together, being embedded in the concrete of the webs.

Chitpore Bridge.

Design.

This bridge (Figs. 11, 12, and 13, Plate 1) is unusual in that it is nearly square in plan. It comprises a reinforced-concrete bowstring or tied arch, having two arch-ribs of 78 feet span and 19 feet 6 inches rise. There are ten bays of 7 feet $9\frac{5}{8}$ inches each. As the bridge has a main central roadway 38 feet 6 inches wide, the main arch-ribs are spaced at 42-foot 6-inch centres. Outside each arch-rib the cantilever ends of the cross girders carry a 9-foot 3-inch outside roadway and a 10-foot footpath. The total width of the bridge is 87 feet 6 inches, so that the width is greater than the clear span.

Arch-Ribs.

The arch-ribs are 3 feet wide, 3 feet 3 inches deep at the centre, and 4 feet deep at the ends. The central portion of the rib is reinforced by twelve longitudinal rods $1\frac{1}{2}$ inch in diameter at the top, in two layers, and twelve similar rods at the bottom. At the quarter-points, where the ribs are 3 feet 6 inches deep, there are twenty-four rods $1\frac{1}{2}$ inch in diameter in four layers at the top, and twenty-four similar rods at the bottom of the rib. At the centre of the span the percentage of longitudinal steel is 3·23, whilst the laterals and bindings add 0·425 per cent. The layers of main longitudinal rods at the top of the rib are wrapped around at intervals of 9 inches with hoops of $\frac{3}{8}$-inch-diameter rods. The main longitudinal rods at the bottom surface are similarly hooped. Sets of six stirrups of $\frac{3}{8}$-inch-diameter rods are spaced at 9-inch centres and bind the two groups of main longitudinal rods together. The maximum stress in the arch-ribs ranges from + 894 to — 352 lb. per square inch.

Tie-Beams.

There are twenty-eight rods $1\frac{1}{2}$ inch in diameter in each of the two tie-beams. Originally it was intended to use lengths of rods welded together, the welds being arranged to break joint. It was, however, found possible to obtain rods of sufficient length in single pieces. These rods extend well beyond the point of intersection of the centre-lines of the arch-ribs and of the tie-beams, and are fanned outwards and embedded in the blocks of concrete at each end of the ribs. The junctions of the arch-ribs and tie-beams are strongly reinforced by shear rods, which hold the foot of the rib to the tie-bar and to the adjacent cross girder of the deck-system. The ends of the arch-ribs are each strongly stiffened against the nearest cross girder by webs which fill in the space between the tops of the bearings and the side of the cross girder.

Overhead Bracings.

It was found possible to provide only two overhead bracings for the Chitpore bridge ribs. These bracings are of H section, with 3-foot by 9-inch flanges and 4-inch webs, and are cambered 1 foot 6 inches at the centre. The flanges are opposite to the four central hangers, and merge into them to form a stiff and rigid frame.

Hangers.

These are 2 feet 9 inches deep by 10 inches wide, of dumb-bell shape with six $1\frac{1}{8}$-inch-diameter rods in each flange. The stress in the steel under full live loading is 6·5 tons per square inch. Under a wind-pressure of 40 lb. per square foot, neglecting the assistance given by the overhead bracings, the wind-stress would be 0·78 ton per square inch in the steel on the tension side and about 100 lb. per square inch in the concrete on the compression side.

Reinforced-Concrete Rockers.

The expansion-end of the bridge is supported upon a pair of rockers or knuckles of reinforced concrete. These rockers are strongly reinforced, and are fitted with caps and shoes of cast iron which engage concave recesses in cast-iron members embedded in the feet of the arch-ribs and in the upper parts of the reinforced-concrete grillages.

Grillages and Distributing Beams.

The grillages carry the weight of the structure and distribute it to the masonry below. They are connected together in pairs by strong distributing girders of reinforced concrete.

Tollygunge Bridge.

Design.

This bridge (*Figs. 14* and *15*, pp. 116 and 117) is of 110 feet span and 27 feet 6 inches rise, and is of the reinforced-concrete bowstring or tied arch type. The span is divided into twelve bays of 9 feet 2 inches each. The bridge carries a 30-foot clear roadway between the two arch-ribs, and two footpaths each 8 feet wide outside the arch-ribs.

Arch-Ribs.

The two arch-ribs, which are spaced at 33-foot 6-inch centres, are 2 feet 6 inches wide, 3 feet 3 inches deep at the centre, and 4 feet 7½ inches deep at the ends. They are somewhat narrow, and it is therefore important that their stability against sideways buckling should be ensured. The ribs at their centre points are each reinforced with six main longitudinal rods 1¼ inch in diameter in the top surface and six similar rods in the bottom surface. Towards the quarter-points in the span, where the bending moments are higher, the main longitudinal rods are increased in number to ten in both top and bottom of the rib, being then arranged in two layers. The rods in each outer layer at both top and bottom of the rib are tied together with horizontal transverse rods ½ inch in diameter spaced at 9-inch centres. Where a second layer of main longitudinal rods is used, the outer rods in these layers are held together by horizontal transverse rods ⅜ inch in diameter at 9-inch pitch. Sets of six stirrups made of ⅜-inch rods are spaced at 9-inch intervals, and connect together across the depth of the rib the rods of the upper and lower longitudinal layers. Along each side of each rib two ¾-inch-diameter longitudinal side rods are used. These are connected together across the width of the rib by ¼-inch-diameter binders spaced 9 inches apart. In each bay of the arch-ribs two frames made of 1-inch square rod are used to hold the reinforcements to proper spacing. These remain in the concrete. The ribs contain 1·70 per cent. of longitudinal reinforcement. The laterals, stirrups and binders add 0·53 per cent. of steel and the spacing frames add another 0·13 per cent., making the total reinforcement 2·36 per cent. The concrete is of approximately 1 : 2 : 4 mix.

Fig. 16 gives the section of the arch-rib at the quarter-point in the span. The maximum stress in the concrete of the arch ribs is + 987 to — 167 lb. per square inch in the middle of the span, and + 916 to — 260 lb. per square inch adjacent to the quarter-points in the span.

Tie-Beams.

The two tie-beams each have twenty-eight rods 1¼ inch in diameter. These were embedded in concrete after the steel was carrying the tension due to the thrust of the ribs under their full load and to the weight of

the deck-system. The tie-beams are 3 feet 6 inches wide, and 15 inches deep at the centre of the span. The tie-beam rods are in single lengths without joints. These rods extend into projections extending outwards 6 feet beyond the intersection-points of the ribs with the tie-beams, and are hooked over 1-inch-diameter transverse anchor-rods in these projections. The tie-beam rods are spread out into a fan at the two ends of the bridge. At the two ends of each rib the foot of the rib is stayed to the end cross girder of the deck by a concrete web 2 feet thick. Twenty-two diagonal shear rods, 1 inch in diameter, set at an angle of about 45 degrees, connect the end cross girder and the lower side of the tie-beam to the upper side of the arch-rib.

Overhead Bracings.

The ribs are 2 feet 6 inches wide and have a length measured along the centre-line of the rib of 125 feet $7\frac{3}{4}$ inches. The ratio of length to width is 50 to 1, so that it does not appear desirable to rely upon the resistance to buckling which is afforded by the stiffness of the hangers alone. The height enables the five central bays of the arch-ribs to be braced, six horizontal transverse members each 2 feet 6 inches deep and 9 inches wide being employed. These members are cambered 9 inches, and are connected to the tops of the corresponding hangers by curved fillets 3 feet deep. They are also connected to each other by webs $3\frac{1}{2}$ inches thick which are lightened by having octagonal apertures 5 feet 6 inches wide left in them.

Hangers.

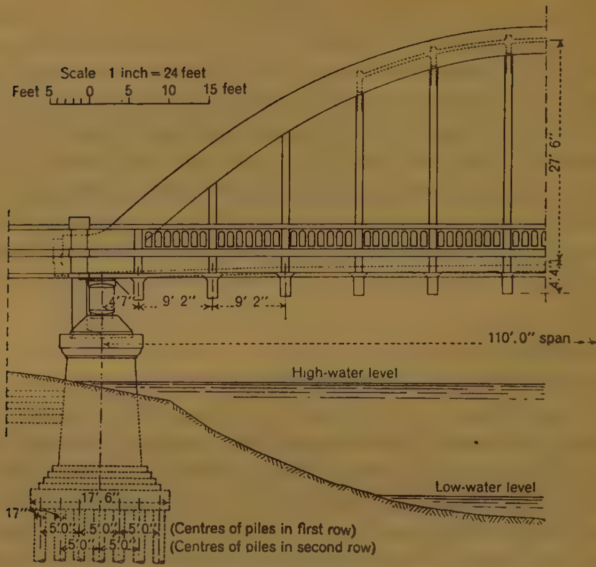
The hangers each have eight rods $1\frac{1}{4}$ inch in diameter, and are of roughly dumb-bell shape in section, 2 feet 6 inches by $10\frac{1}{2}$ inches overall dimensions at base, with four $1\frac{1}{4}$-inch rods in each flange or swell.

Assuming for the purpose of calculation that the overhead bracings do not reduce the stresses in the hanger, or affect the length of the lever-arm with which the wind-stresses in the rib and hanger and the buckling stresses in the rib act, the following are the stresses in the steel and concrete of the central hanger :

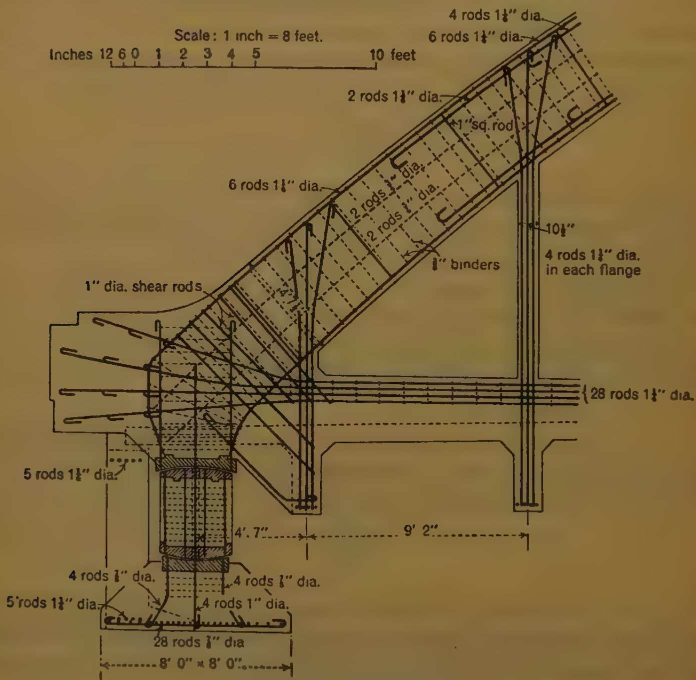
	Steel: tons per square inch.	Concrete: lb. per square inch.
Under maximum direct live and dead loading . . .	6·05	nil
Under 40 lb. per square foot wind-load	2·07	240
Totals . . .	8·12	240

These central hangers, which are the tallest, will of course be assisted by the other hangers, and, the average wind-stresses on the hangers being only perhaps 75 per cent. of the above, the stresses in the central hangers will be reduced by possibly 15 per cent.

Figs. 14.



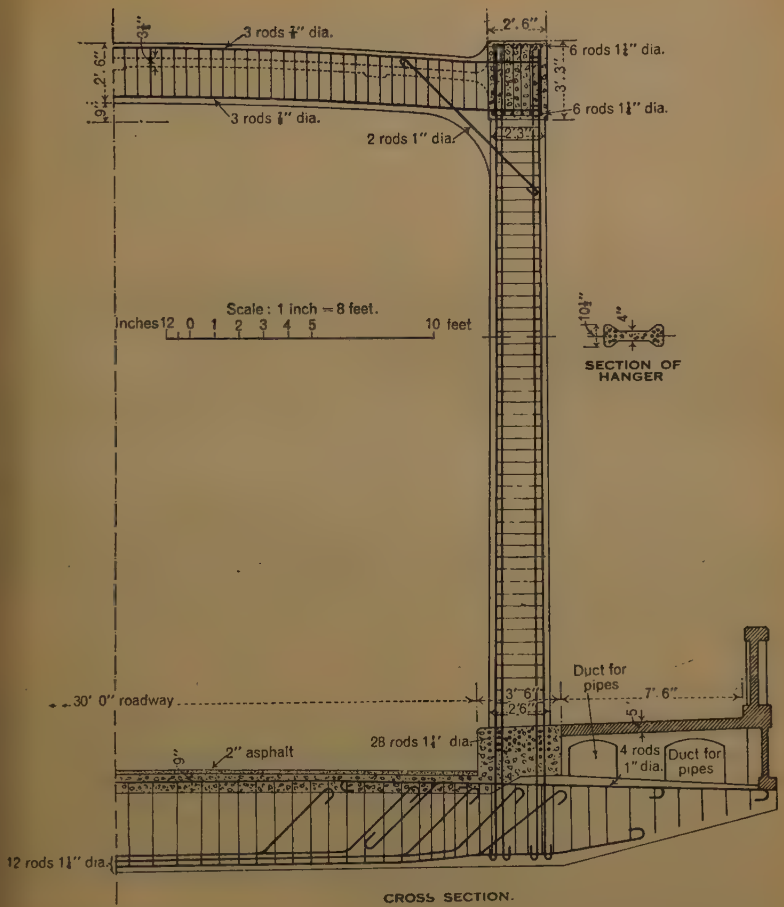
GENERAL ELEVATION.



LONGITUDINAL SECTION OF RIB.

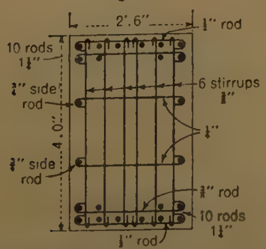
TOLLYGUNGE BRIDGE.

Fig. 15.



TOLLYGUNGE BRIDGE.

Fig. 16.



SECTION OF TOLLYGUNGE BRIDGE ARCH-RIB AT QUARTER-POINT OF SPAN.

Expansion-Arrangements.

The bridge is placed on reinforced-concrete rockers somewhat similar to those used for the Chitpore bridge. The rockers are pierced with 3-inch-diameter holes on their centre-lines, through which holding-down bolts pass from the foot of the arch-ribs into the grillages below. These holes are filled with bitumen, so as to allow movement of the rockers.

General Remarks on Bowstring Bridges.

Overhead Bracings.

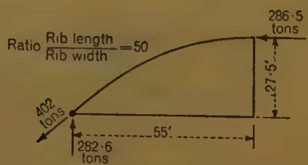
It is the Author's view that in many reinforced-concrete bowstring bridges the overhead bracings are inadequate, and far too much reliance is placed upon the stiffness of the hangers. It is not so much a matter of calculation as a matter of judgement and sense of fitness that is needed to arrive at the strength of the hangers or verticals and the design of the overhead bracings which will give adequate lateral stiffness to the ribs. The Author feels that the provision of substantial overhead bracing gives a rigidity and general stability to such bridges which is desirable and well worth having. In the three reinforced-concrete bowstring bridges described, strong overhead bracings have been introduced and the hangers are made very stiff in the direction perpendicular to the plane of the arch-rib and tie-beam.

Buckling Stresses in Arch-Ribs.

In designing the arch-ribs it is important to consider the buckling forces, but difficult to estimate the value to be assigned to them. The Author has been in the habit of estimating them as a load acting laterally upon the side of the arch and dependent in value upon the maximum horizontal thrust carried by the arch-rib. The lateral loading is taken as 4 per cent. of the horizontal thrust in the rib, and is assumed to be uniformly distributed over the length of the rib.

In the case of the Tollygunge bridge the maximum direct horizontal thrust on the rib (*Fig. 17*) is 286·5 tons. The length of the rib measured

Fig. 17.



along the curve is 125·64 feet. The rib is divided into twelve bays, and the buckling load per bay is therefore taken as $\dfrac{286{\cdot}5 \times 4}{100 \times 12} = 0{\cdot}95$ ton.

As the rise of the arch is 27·5 feet, the lever-arm of the buckling force is 27·5 feet at the centre of the span for the central bay. The overturning moment is $0·95 \times 27·5 = 26$ foot-tons. If the rib were kept in line by the stiffness of the hangers alone, the approximate stresses in the central hangers under these buckling loads would be 2·76 tons per square inch tension in steel and 320 lb. per square inch compression in concrete. In the Chitpore bridge, by a similar calculation, the tension on the steel of the hangers to resist buckling of the arch-ribs will be 1·6 ton per square inch, whilst the compression on the concrete of the hanger will be about 202 lb. per square inch; in the Alipore bridge the corresponding figures are about 2·81 tons per square inch and 260 lb. per square inch. It is, of course, to be assumed that an arch-rib will itself offer a considerable resistance to buckling; it is difficult to say what the factor of safety is.

It should be noted that the buckling loads and stresses are those calculated with the maximum loadings on the whole bridge. Under these conditions the maximum direct live-load stresses are not developed in the hanger-steel, being only developed when the maximum possible concentration of load which it is possible to concentrate upon one bay of the deck is placed upon the hanger. Further, the maximum loading on the bridge will not occur when a storm with wind-velocities of 110 miles per hour is blowing. The hangers are not likely to be called upon to resist maximum buckling stresses at the same time as high wind-stresses.

The addition of overhead bracings to a bridge, if sufficiently substantial, will undoubtedly help to reduce both the wind-stresses and also the buckling stresses and will give a solidity to the structure which it would not otherwise have. Such additions do not add very largely to the cost of the structure. For example, the costs in two of the bridges discussed were as follows:—

	Total cost of bridge: £.	Cost of bracings: £.	Cost of bracings: per cent.
Chitpore bridge . .	10,000	160	1·6
Tollygunge bridge . .	8,000	125	1·6

A further advantage of substantial overhead bracings is the security they give during the erection of the bridge. It is often desirable to strike the wedges under the arch-ribs before the structure is complete in all details. In the bowstring bridges, before easing the arch-ribs or removing the wedges supporting them, the bracings were concreted with the exception of narrow gaps where they were connected to the arch-ribs, these gaps being spanned by the bracing-reinforcements so that they acted as hinge-points. The hangers opposite to the flanges of the overhead bracings and the cross girders to which they were connected were also concreted before the arch-ribs were eased off. Usually by that time the deck-slabs of the roadways had been completed, and hence the frames which the bracings, hangers and deck-system formed assisted in bracing the arches at a rather critical period in the erection of the bridge. The hangers to

which no overhead bracings were attached were usually concreted last of all, after the deck-system and all possible loads to be supported by the hangers were being carried by the steel reinforcements of the hangers. The tie-beams were also concreted at a late stage in the construction of the bridge, when they were stressed as much as possible by the dead loads.

The Paper is accompanied by nineteen drawings, from some of which Plate 1 and the Figures in the text have been prepared, by forty-nine photographs, and by the following Appendix.

APPENDIX.

CARRYING-POWER OF RAFT ON GROUP OF PILES.

It is proposed to consider one foundation as a whole, to arrive at conclusions as to the carrying-power of the group of piles used.

Taking one foundation of the Beliaghatta bridge (*Fig. 18*, p. 122), the following are the thrusts and loads :—

Horizontal thrust from seven arch-ribs :—

Under dead loads	1,412 tons.	
Under live loads without impact	672 ,,	
Total . .	2,084 tons, applied at the pins of end hinges.	

Vertical loads :—

Half weight of bridge superstructure	757 tons	
Live load on half bridge (no impact)	315 ,,	
		1,072 tons.
Dead weight of concrete, etc., in one abutment .	1,480 tons	
Weight of earth filling	2,900 ,,	
Live load on abutment	147 ,,	
		4,527 ,,
Total dead load on raft		5,599 tons.
Weight of 137 piles	500 tons	
Weight of consolidated earth engaged by the pile-group	10,000 ,,	
Weight of wedge of earth resting against back batter piles	1,960 ,,	
		12,460 ,,

Area of raft 90 feet by 49 feet = 4,410 square feet.

Area over which loads are distributed at level of points of piles 90 feet by 65 feet = 5,850 square feet.

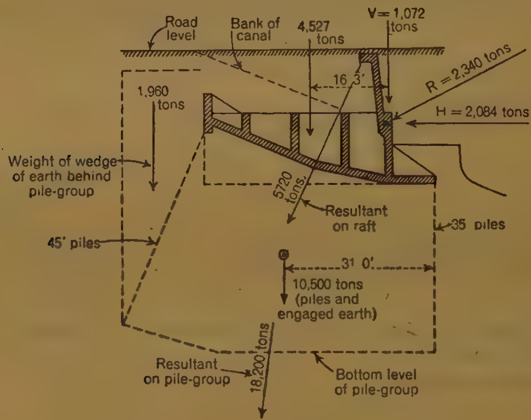
The resultant pressure on the hinge-pins is 2,340 tons. The resultant pressure on the base of the raft is approximately 5,720 tons, applied practically at right angles to the slope of the raft and passing practically through the centre of the foundations. The resultant at the level of the bottom of the piles is approximately 18,200 tons.

The pressure at the lower surface of the raft is $\frac{5,720}{4,410} = 1 \cdot 3$ ton per square foot, which is somewhat lower than the value of 1·5 ton per square foot found at this level when considering the loads on a more heavily loaded central strip of the raft.

The pressure at the base at the level of the bottom of the piles, considered as merely carried by the subsoil below without any other help, is $\frac{18,200}{5,850} = 3 \cdot 1$ tons per square foot. It is very difficult to decide what the original pressure at this base-level was under the old bridge. Over the greater part of the central portion of the present foun-

dations the original approach-bank of the bridge existed, the surface of which was over 60 feet above the level of this base. Towards the two side edges of the foundations the original approach-bank sloped down, and its surface was probably 52 feet above the base-level. That 52-foot depth was taken previously in considering the depth of the toes of the piles. Apparently the mean pressure over this base-area under the original superimposed earth loads was about 2·55 tons per square foot. The site must have been well consolidated, as the bridge which was replaced was more than 60 years old.

Fig. 18.



Mr. J. P. Porter has suggested [1] that the ultimate supporting power of a group of piles is to be ascertained by taking the bearing resistance per square foot at the foot of the pile-cluster calculated by the formula

$$\sqrt{l} \times \frac{w}{2,240}\left(\frac{1+\sin\beta}{1-\sin\beta}\right)^2,$$

considering this as being developed over the whole area, and adding thereto the frictional resistance of the mass to movement. In the case under discussion, the bearing resistance at depth $l = 52$ feet when $w = 110$ lb. per cubic foot and $\beta = 19$ degrees is 1·37 ton per square foot; if l be taken as 60 feet the bearing resistance rises to 1·47 ton per square foot. Probably the average bearing resistance for the whole area may reasonably be taken as 1·44 ton per square foot. The frictional resistance of the mass of the foundations to downward movement varies as the depth (upon which the lateral pressure of the soil depends) and as the area along which sliding takes place. The lateral pressure at any given point in tons per square foot is given by the expression

$$\frac{w}{2,240}\left\{\frac{1-\sin\beta}{1+\sin\beta}\right\} \times l,$$

where l denotes the depth of the point in feet below the surface.

The maximum depth at the front of the foundation is 42·5 feet, at the rear of the

[1] "The Supporting Value of Piles and Other Deep Foundations." *Concrete and Constructional Engineering*, vol. 31 (1936), p. 319.

foundation it is 57 feet, and the average depth at the two sides is 50 feet. The lateral pressures will vary from zero at the top of each surface along which sliding may take place to maximum values of 1·06, 1·42, and 1·25 ton per square foot at the front, back, and sides respectively.

The ultimate frictional resistance will be ($\mu \times$ area $\times \frac{1}{2}$ maximum lateral pressure), and is approximately as follows:—

Front	$0{\cdot}344 \times 42{\cdot}5 \times 90 \times 1{\cdot}06 \times \frac{1}{2} =$	694 tons.
Back	$0{\cdot}344 \times 57{\cdot}0 \times 90 \times 1{\cdot}42 \times \frac{1}{2} =$	1,260 ,,
Two sides	$2 \times 0{\cdot}344 \times 50 \times 65 \times 1{\cdot}25 \times \frac{1}{2} =$	1,400 ,,
	Total frictional resistance	3,354 ,,
	The ultimate bearing resistance is $1{\cdot}44 \times 90 \times 65 =$	8,400 ,,
	Total . .	11,754 tons.

The ultimate supporting power thus deduced is only $\frac{11{,}754 \times 100}{18{,}200} = 65$ per cent. of the actual loading, equivalent to $\frac{11{,}754}{5{,}850} = 2{\cdot}0$ tons per square foot at the level of the base of the piles, whereas the actual loadings on the subsoil at the base-level considered varied from 2·55 to nearly 3·0 tons per square foot before the site for the bridge-foundations was disturbed.

It appears to the Author that the theory discussed above is not satisfactory for conditions such as obtain in Calcutta as, obviously, the subsoil below the base-level of the piles can sustain as great a load as it has been sustaining for the last 60 years, and probably a moderate amount more.

A point which does appear from a consideration of the supporting power of a group of piles is that a relatively few very long piles are considerably more effective than a larger number of shorter piles. Further, it may be of considerable advantage to drive the outer piles in a large piled foundation so that they are in zig-zag lines, as by this means a greater area for developing frictional resistance to settlement may be obtained.

Discussion.

Mr. M. R. Atkins showed a number of lantern-slides illustrating the bridges described in the Paper.

Mr. F. C. Cook remarked that there were many points in the Paper which would be of value to engineers engaged in similar work in Great Britain. The method adopted at Dum Dum of skidding the old bridge sideways in order to provide a temporary crossing during the building of the new structure was interesting, and was both simple and effective. How far had the old bridge been moved, and what had been the cost?

Three-hinged reinforced-concrete arches were not very common in Great Britain, but there were interesting examples, amongst others, at Twickenham, and at Oich and Grantown-on-Spey in Scotland. The horizontal thrust of each of the arch bridges at Calcutta was provided for by a vertical thrust-surface (p. 97 and Fig. 5, Plate 1), in addition to sloping the foundations and inclining a number of the piles. The last two methods were common practice, but he thought that the provision of a thrust-wall was novel. It was stated that those precautions were successful in preventing horizontal movement of the abutments, despite the occurrence of appreciable vertical settlement. Perhaps the Authors would say whether the measurements that had been taken were sufficiently precise to rule out the possibility of such movement as might introduce passive pressure.

Bowstring bridges of reinforced concrete in Great Britain had been most commonly of spans of about 100 feet, and he agreed with the Authors that "the provision of substantial overhead bracing gives a rigidity and general stability to such bridges which is desirable and well worth having." It was unfortunate, however, that such overhead bracing gave bridges of that size a somewhat clumsy appearance when looked at from the road. There was room for improvement in that respect. Two 100-foot span bowstring bridges had been constructed about 5 years ago on the Glencoe road in Scotland, and had been provided with rockers somewhat similar to those shown by the Authors. Had the Authors made any measurements of the movement of the rockers and of the seasonal expansion of the structures themselves? An interesting and ingenious feature of the Alipore bridge was the raising of the footpath about 5 feet 6 inches above the roadway-level in order to accommodate a large water-main. The cross section of the Chitpore bridge showed a 9-foot 3-inch carriageway and a 10-foot footpath on each side outside the main ribs, in addition to a central carriageway of 36 feet. That seemed unusually generous, and it would be interesting to know what was the actual or potential traffic for which provision had to be made. For the Tollygunge bridge reinforcing bars had had to be brought to the site doubled for ease of shipment. Presumably they had had to be heated again for straightening before

being used in the work, and perhaps the Authors would say whether they had apprehended or observed any ill effects on that account. It was interesting to notice that the working stresses used in the concrete had kept pace with those usually followed in British practice, and that in at least four of the bridges referred to the Authors had allowed for even a slightly heavier standard load than that adopted in Great Britain.

On p. 118, dealing with the design of the arch-ribs, reference was made to a hypothetical lateral load equal to 4 per cent. of the horizontal thrust in the rib. What were the considerations that had led the Authors to adopt that figure?

The plea was sometimes advanced that lack of suitable labour prevented the adoption of a particular form of construction which would of itself be economically advantageous. The present Paper, which described the methods adopted for the erection of really complicated structures, was a tribute to the thoroughness of the supervision that had been employed, in view of the fact that only unskilled Indian labour had been available. The Authors might well be satisfied that in such circumstances no defects had yet become apparent in the considerable period since the completion of most of the bridges described.

Mr. C. H. Bompas congratulated Mr. Atkins on his work of 17 years as Chief Engineer of the Calcutta Improvement Trust, which Mr. Bompas himself had served for 10 years as its first Chairman. The Trust had been formed to rebuild and extend Calcutta, the insanitary condition of which had attracted attention during very serious outbreaks of plague. In the course of that work it had been found necessary to provide proper roads out of Calcutta. Calcutta was built on the left bank of the Hooghly, which was one of the outlets of the Ganges and had the usual characteristics of a deltaic river; the ground was highest on its banks and fell away from the river, so that the natural drainage flowed away from the river instead of towards it. The Circular Canal to which reference had been made took off from the Hooghly and ran round the north-east side of Calcutta for about 2 miles, passing through a district where the ground-level was low and the subsoil-water at most times of the year was almost on the surface. Engineers would therefore realize how difficult it had been to provide secure foundations for bridges over that canal. He had known the municipal engineer to experience the greatest possible difficulty in putting in an ordinary main sewer a few feet down in that neighbourhood, on account of quicksand. It was extremely important to have adequate bridges over the Circular Canal and over Tolly's Nullah (which was the old bed of the Hooghly), since the former cut off access to Calcutta from the north and east, and the latter divided the docks from the city. Those remarks might give some idea of the surroundings of the problem with which the Authors had had to deal. It would be a matter of satisfaction to Mr. Atkins, after completing his service with the Trust, during which he had had to deal with almost every branch of engineer-

ing, that he had placed on record that section of his work which consisted in providing bridge exits all round Calcutta.

Dr. Oscar Faber remarked that in his opinion the bridges were thoroughly well designed, and exactly fulfilled the conditions for which they were provided. In reading the Paper with a view to discussing it, he had only found one or two minor points to which reference might be made in a spirit of inquiry.

The cross bracing shown in Figs. 3, Plate 1, seemed perhaps a little unnecessarily ample, and he thought that probably half of the members could have been omitted without detriment to the bridge, remembering that reinforced concrete was good for tension as well as compression.

His firm had constructed several bowstring girders somewhat similar to those described, and had found them to be rather expensive in shuttering, as a considerable amount of shuttering of a costly type was required. It seemed to him that the choice of the bowstring design was entirely justified in the case of the long-span Alipore bridge (Fig. 8, Plate 1), but he would like to ask whether the Authors were quite satisfied that the expense was justified in the case of the Chitpore bridge (Fig. 11, Plate 1), where the span was only 78 feet, which was less than the width of the bridge. Would it not have been at least as economical, and possibly more so, to have run continuous longitudinal girders and to have eliminated the bowstring arch? The continuous girders would have obviated the necessity of providing cross girders, each of which had to be designed for the full load. He was disposed to think that that design would have been just as economical and rather easier to construct; there would have been a great deal less falsework, and the work could have been done without taking up any more headroom underneath the bridge, which might have been an important consideration. The completed bridge would have been a little less obtrusive, but whether that was an advantage or not he was not sure.

On p. 106 the Authors gave a method of calculating the bearing pressure at the toe of a pile by a formula which seemed to be based on Rankine's formula, and they arrived at the very low result of 5·7 tons where the skin-friction was 23·6 tons. He had been doing a good deal of research on the bearing pressure and frictional resistance of piles, and in most of his tests he had found that the end bearing resistance had very much higher values than any value that would be deduced from Rankine's theory, owing, he thought, to the consolidation of the ground during pile-driving. In some cases pressures had been developed of 60 tons per square foot in ballast, where in the unconsolidated condition previous to pile-driving the ground would have safely carried only from 5 to 10 tons per square foot. Undoubtedly, therefore, the effect of consolidation due to pile-driving was very considerable, and it did not appear to enter into the formula given on p. 106. Had the Authors taken into account the consolidation due to driving, and did they think that there was a possibility that the end bearing resistance might in fact be somewhat greater? The suggestion

that it might be was further confirmed by examination of *Fig. 18* and the Appendix (pp. 121–123), where the Authors calculated that the total pressure on the total area of soil contained within the piles was, as they themselves mentioned, lower than that which the ground had already carried due to the superimposed earth. That gave colour to the suggestion that the consolidation under the ends of the piles might have justified a slightly higher bearing pressure than was deduced from the formula to which he had referred.

Mr. G. F. Walton remarked that the Paper was of especial interest to him, as he had been responsible for the construction of the five bridges built by Messrs. Bird & Co., and had also built other bowstring and arch bridges of larger span in the same district. The costs given on p. 101 would be more useful if more information could be given. The total cost was given as £240,000, which was £95,000 more than the cost of the individual bridges; did the latter figure include the cost of the approaches and of the temporary bridges? It would be convenient if a summary were made showing the cost per square foot of clear span for (*a*) the bridge proper, including foundations, and (*b*) the approaches, excluding the cost of land purchased. From those figures he was quite certain that it would be obvious that the bowstring girder would prove the more economic for such conditions as the deltaic soils in Calcutta, or even elsewhere unless there were very good foundations for the arches. Mr. Atkins stated on p. 97 that the bowstring girder might have received more consideration for the first four bridges had it been better known. Perhaps it might have been more favourably viewed if the minimum crushing strength of concrete based on local conditions and experience had been more convincingly known, so that higher working stresses might have been used. On p. 104 Mr. Remfry referred to a working stress of 600 lb. per square inch for the Dum Dum bridge; he had specified a crushing strength of 2,000 lb. per square inch at 28 days, and as a result of the crushing strengths obtained during the construction of the earlier bridges the specified strength had been raised to 3,500 lb. per square inch for the Alipore bridge, and the working stress to about 700 lb. per square inch. The original proposal was to use steel for the Alipore bridge. The first design and tender for a bowstring girder in concrete had been submitted by Mr. Walton on behalf of Messrs. Bird & Co., and was eventually accepted by the Improvement Trust, with some modifications on the advice of the Authors. That was only possible because of the higher stresses that could be allowed as compared with the earlier bridges. He emphasized that point because he was of opinion that the best use was not always made of concrete. Mr. Remfry referred also on p. 104 to stresses of 765 and 985 lb. per square inch, but those figures were presumably for concrete suitably hooped; it would be of advantage if that point could be made clear. In the case of another bridge built later by Messrs. Bird & Co. stresses of up to 1,050 lb. per square inch inside spiral reinforcement and 795 lb. per square inch in ordinary concrete had been employed, the proportions of the concrete

being rather richer. An eminent French engineer, M. Lossier, had designed an arch bridge for Dinard with two spans, each of 1,508 feet, in which a working concrete-stress of 2,150 lb. per square inch and a crushing strength of 6,300 lb. per square inch were allowed. It was important that all unnecessary weight should be eliminated; the deck-slab should be as light as possible, and it was desirable to use arch-ribs of box or dumb-bell section, even though the extra shuttering hardly seemed to be justified.

In all the bridges described in the Paper the centering had been carried on steel girders, generally supported by screw piles or timber piles; in some cases cribs had been used, but he did not like that method. He would like to see, in connexion with larger bridges than those described, whether it would be possible to use steel-arch centering. He had done that in the case of a 300-foot single-span bridge, the centering being preloaded with sandbags equal in weight to the concrete, which were dropped off as the concrete was placed, thus eliminating any permanent set. The weights which had to be dealt with should be appreciated, as it was by no means easy to support a weight of several hundred tons 100 feet up in the air with very little lateral support.

He was not altogether disposed to agree with the Authors that settlements such as were referred to in the Paper had really occurred, but he felt that if such settlement had taken place there was certain to have been some spreading of the arches.

In connexion with the concreting of the tie-bars, there was a point of considerable importance which should be considered when designing a bowstring girder; to make it clear, it was necessary to describe the details of building and concreting the tie-bars. The tie-bars were in the form of 6-inch by 1-inch or 8-inch by 1-inch flats, with steel plates at the ends. In the case of a bowstring girder of about 220 feet span, there would be a movement of about 2 inches on the rockers when the dead load was put on the tie-bars. To construct the bridge, the tie-bars were first placed in position; the rib steel was then fixed, and after the shuttering had been done the tie-bars had to be concreted to the arch-ribs. In that process a considerable length of each tie-bar was concreted, and the rest of the tie-bar was not concreted until after the whole load was put on. Torsion was thus apt to be set up around the junction of the tie-bar and the arch, because the arch was in compression and the tie-bar was in tension. The point needed careful consideration, but he thought that the difficulty could be overcome by extra steel in the haunches, or by wrapping suitable material round the tie-bars so that the lengths inside the concrete could slip and so eliminate the torsion.

Steel centerings for arches formed a very good method of dealing with roofs or hangars with spans of up to 150 or 200 feet, because whatever the rise was, and however high off the ground the arch was, the cost would vary very little; it chiefly depended on the number of times that the centering could be used.

Mr. E. J. Buckton observed that the arch was one of the most beautiful types of bridge, and should be adopted as often as possible, but it had to have a very good foundation, preferably on rock. The formation at Calcutta was really most unsuitable for arch bridges. His firm had recently made some tests by loading the floors of trial pits in Calcutta, and there was always a definite settlement for any load, however small. The results obtained so far showed that in places the subsoil would probably take 2 tons per square foot, giving a design load of about 1 ton, which more or less agreed with the figures given in the Paper.

Figs. 5 and 8, Plate 1, showed rather an interesting comparison of foundations, Fig. 5 being that for a three-hinged arch and Fig. 8 that for a bowstring bridge. The former required about twice as many piles as the latter; it was much more complicated, and included battered piles, which were always difficult in construction. The Authors stated on p. 101 that the costs there given "cannot be accepted as giving a true measure of the relative cost of the different types of bridges, as the cost of labour and materials was high when the arch bridges were built, and the cost of the bowstring bridges was reduced by keen competitive tendering." Actually, he believed that the tendering for the first arch bridge had been very competitive; it was very low, and he believed that the contractor lost money on it. In any case, however, from the average cost of £28,000 for the arch bridges, as compared with £15,000, £10,000, and £8,000 for the bowstring bridges, and from the diagrams of the foundations in Figs. 5 and 8, Plate 1, it appeared that the arch bridge was not an economical type to adopt in such ground as existed in Calcutta. The vertical settlements were given as ranging from a fraction of an inch to 5 inches. It would be interesting to know a little more about the movements of the abutments, because 5 inches was an appreciable settlement. If it were uniform it would not matter very much, but if one corner of an abutment did not move and the other went down 5 inches there would be a very severe racking of the superstructure. He thought that it was safe to say that arch bridges on such foundations, if made technically sound, became economically unsound.

The Chitpore bridge (Figs. 11 to 13, Plate 1) had a span of 78 feet and an overall width of about 88 feet. The bowstring type had been adopted, with roadways cantilevered on each side. He did not think that the design was attractive, and he was sure that it was not economical. The alternative, he suggested, would be a deck bridge with girders at about 5-foot centres. The construction-depth would not have to be any greater, so that there would be the same headroom, and it would not be necessary to alter the grades of the road. Such a bridge on that site would have been cheaper and simpler to construct.

The Paper dealt rather fully with overhead bracing. He felt that such bracing was usually rather ugly, especially on a skew bridge, and Mr. Cook appeared to share that view. The Paper emphasized that it was necessary,

but in Mr. Buckton's view it was very often quite unnecessary for small bridges such as those described. There was no structural case for overhead bracing in such bridges of spans less than 120 feet, and it could usually be safely dispensed with in spans of up to 150 feet. It was necessary to obtain lateral fixity for the bow ends, but that could be done by a deep end cross-girder at the abutments; alternatively, if a flexible bearing wall were used instead of rocker bearings, the fixity could be obtained easily and cheaply. Had there been any trouble with the hangers? They might have suffered distortion by the deck deflecting while the arch-ribs were restrained by the overhead bracing.

The raking piles in the foundations were shown as being driven at an angle of 23 degrees. Had any real difficulty been encountered in driving them to that rake? It was a very big angle, especially for "Vibro" piles.

The four arch bridges had been designed in 1920–1923, 15 to 18 years ago, which was a long time in the history of reinforced concrete, and the Authors were at a great disadvantage in describing works so long after they had been designed, because it made adverse criticism comparatively easy. He had been in Calcutta in April 1936, and, being interested in the design for a large-scale reinforced-concrete structure in the district, he had wished to study the practical capabilities of the Indian in that class of work, as he knew from experience that reinforced-concrete work abroad could be really appalling if the local labour were inexperienced. He had been fortunate in being shown the bridges described in the Paper, two of which had been still under construction, and he had been most favourably impressed by the quality of the work that he saw; much care and trouble must have been taken by those in charge to obtain such satisfactory results. He would like to congratulate the Authors on producing reinforced-concrete work of such excellent quality.

Mr. F. C. Temple remarked that he had from time to time watched the construction of the very successful bridges described, and had observed the development of concrete work in Calcutta from a period very much earlier than that. In 1906, when he had first proposed to put in window-heads in blocks of concrete alone people had been inclined to think that he was mad; they had been frightened to employ cement, and not unnaturally, because it had in the past been used so extremely badly.

He regretted that Mr. Atkins, when discussing the bridges, had not mentioned the Franki pile, which was one of the latest developments he had used in Calcutta, because he was of the opinion that it was going to prove the best foundation possible in deltaic soil. Engineers who had never seen soil of that kind could have no idea how little bearing power it had. In many parts of Calcutta there was a crust close to the surface which would carry a certain load, but if by accident that crust were penetrated, even when putting up a light structure, great difficulties were met with. He had taken a 12-foot length of $1\frac{1}{2}$-inch pipe standing on end and shaken it, and with its own weight it had gone right down into the ground.

Mr. M. R. Atkins, in reply, expressed his appreciation of the way in which the Paper had been received. Mr. Cook had asked about the skidding of the old bridges. They had been moved about 80 feet, and could have been moved further just as easily had that been desired. As the bridges had a tendency to move in jerks when the strain was put on the hauling tackle, it had been necessary to proceed very carefully, and not to let one end get ahead of the other. The cost of the shifting operation was very small. He regretted he could not give the actual figures; they were included in the cost of the temporary bridges.

Mr. Cook also raised the question whether the measurements taken were sufficiently precise to rule out the possibility of horizontal movement having taken place at the abutments of the arch bridges. It might answer several speakers if Mr. Atkins gave some figures, which were all that he had been able to collect, with regard to the settlement of the abutments. It was very difficult to tell what had actually happened during construction, but he had some records of what had happened after construction. In the case of the Dum Dum bridge, between 1925 and 1927 the abutments sank an average of 3¼ inches. Mr. Buckton had presented an alarming picture of what might have happened if one corner of an abutment had not moved and another corner had gone down 5 inches, but fortunately the abutments had gone down evenly, as buildings did in Calcutta. In any case the rafts were very strongly reinforced; the bottom surface of each contained a number of 1⅝-inch bars, and he did not think that there was much likelihood of such a raft breaking across under any stresses to which it was likely to be subjected. The crown of the Dum Dum bridge went down 4¼ inches in those 2 years, or 1 inch more than the abutments. That was an indication that there was some spreading of the abutments. It was not possible to measure the movement with the apparatus available, but it was clear that there had been some definite outward push. From 1928 to 1936 the abutments sank a further ⅜ inch only, which meant that they had practically come to rest, but the centre of the span went down 1½ inch, indicating that spreading had continued, and might continue further. It was nothing to be frightened about, because the rate of movement was obviously getting very much slower as the thrust-surfaces and the inclined piles took their load. There was nothing to crack, and another inch or two drop at the crown would not matter. The Manicktola bridge was quite satisfactory. From 1930 to 1936 there was no appreciable sinkage of the abutments, but a sinkage of ½ inch at the centre, which was to be expected as a result of the contraction of the concrete. At Beliaghatta, where trouble had been anticipated and a good many extra piles had been put in, there had been no sinkage at the abutments in those 6 years, and only a bare ⅝ inch at the centre. At Narkeldanga, where "Vibro" piling had been used, there had been no measurable settlement of the abutments from 1931, the year of completion, to 1936, but there had been a 2½-inch settlement at the crown. That showed that there had been

a slight spreading of the abutments, and he accounted for it by the fact that on one side of the canal the ground had been disturbed at the back of the thrust-wall by the construction of a large brick sewer about 50 or 60 years ago, and therefore the ground was not so solid as it was at the other bridges. In the case of the bowstring bridges no serious movements of the abutments were expected. At Alipore from 1932 to 1936 there was a sinkage of barely $\frac{1}{4}$ inch at the abutments and $\frac{5}{8}$ inch at the centre. There were no records as yet relating to the other two bridges. No measurements were available of the movements of the rockers or the roller ends. There was, of course, seasonal movement, but he had no figures indicating its extent.

The reason for the 9-foot 3-inch carriageways outside the main girders at the Chitpore bridge was to provide for bullock-cart traffic, which was extremely slow, and had to be separated from the motor traffic. Provision for four lines of traffic was required in the central roadway, as the bridge was on the line of one of the important new roads to which Mr. Bompas had referred, and would have to carry most of the future traffic between Calcutta and Barrackpore.

The tie-bars at the Tollygunge bridge, which had been shipped bent double, had not to be heated again; they had been bent round a fairly wide arc, and it had been possible to straighten them out cold.

Regarding the buckling stresses in the ribs, the figure of 4 per cent. of the horizontal thrust had been adopted by Mr. Remfry ever since a discussion had taken place before The Institution on the strength of long struts, at the time of the collapse of the first Quebec bridge. At that time it had been suggested that if the lacings in a strut were sufficiently strong to carry a uniform lateral load equal to 4 per cent. of the end load, the strut would be sufficiently strengthened against buckling.

Both Dr. Faber and Mr. Buckton expressed the opinion that the Chitpore bridge might have been more economically designed as a deck bridge with longitudinal girders only. The main question there was one of headroom. There was barely room for a man to stand up on the canal tow-path, and the Irrigation Department refused to give the engineers another inch. As a matter of fact, the bridge had been designed originally as a steel bridge, but Mr. Walton's firm had put in an alternative design in reinforced concrete, which had been adopted. Mr. Atkins quite realized that the longitudinal-girder type might have been more economical, but it had been rejected because its adoption would have meant raising the roadway and altering the layout of the existing abutments.

Dr. Faber also referred to the end bearing resistance of the piles. It was rather striking that the end bearing resistance worked out at only 5·7 tons, when the frictional resistance amounted to 23·6 tons. Mr. Atkins' own view was that the consolidation under a pile varied greatly in different subsoils.

Mr. Walton asked that more information might be given as to the cost of the bridges. Mr. Atkins could not give the costs of the foundations

separately, except in the case of the Alipore and Tollygunge bridges, where they were as shown :—

	Total cost of bridge.	*Cost of foundations and abutments only.*
Alipore	£15,000	£4,900
Tollygunge	£8,000	£2,400

He would endeavour to obtain details of the cost of the temporary bridges and approaches and to include them in his reply to correspondence on the Paper.[1] The total costs given in the Paper did not include the permanent approaches; those were constructed later, and involved extensive road-widening operations which were beyond the scope of a Paper on bridges.

Mr. Walton had raised a very important point with regard to the working stresses. In the case of the first bridge, the concrete had been specified to have a compressive strength of 2,000 lb. per square inch in some parts of the structure and 2,200 lb. in other parts. In the latest bridge, the specification required 3,250 lb. per square inch as the minimum strength, and 3,750 lb. as the expected average. Actually in some of the tests results of over 5,000 lb. per square inch were obtained. One concrete cylinder was made every day, and every third cylinder was tested; if that failed, the other two were tested. The stresses in the arch-ribs to which Mr. Walton referred, 765 lb. per square inch in the earlier bridges and 985 lb. per square inch in the later bridges, applied to portions of the rib where there was lateral binding to assist the concrete, but no spiral hooping. The provision of adequate reinforcement to take up the local stresses at the junction of the tie-bar and arch-rib was a matter of great importance, especially for the larger spans. Diagonal shear rods had been put in across the bottom end of the rib and the tie-bar to deal with those stresses as far as possible. In the Tollygunge bridge, there were twenty-two 1-inch bars at the end of each rib.

He agreed with much that Mr. Buckton had said in his interesting comparison of the arch design and the bowstring design, and he did not think that the arch design would again be adopted. There were several reasons, however, for its original selection. There had been strong opposition at the time to any kind of bridge which would have girders projecting above the roadway; it was desired therefore to have the open roadway which was obtained with the arch bridge. Moreover, at the time the Dum Dum bridge was built the idea was to build it in sections. It had seven ribs, and the intention had been to construct three ribs first and to divert the tramtrack on to them, making a temporary road in that way, and then to build the other four ribs and join up between. Tenders had been called for on that basis, but none had been received, and it therefore became necessary to reconsider the position. He realized that it was asking a good deal of the contractors to expect them to construct a portion of the permanent bridge within 9 feet of an old bridge which was still in use. It

[1] To be published in the Institution Journal for October, 1938.—Sec. Inst C.E.

had therefore been decided to shift the existing bridge in the way described in the Paper and to use it as a temporary bridge, and to call for tenders for constructing the whole of the new bridge in one operation. The fact that the designs had been got out on the basis of an arch bridge, and had been approved by the contributing authorities after much discussion, had been a strong reason for going on with the arch bridge design, instead of putting the whole matter in the melting pot and re-designing the bridge.

He agreed that the overhead bracing was ugly, and he was interested to hear that Mr. Buckton thought it unnecessary for spans such as those in question. No doubt Mr. Remfry would have a good deal to say on that point; Mr. Remfry thought that it was necessary, for reasons which it was not difficult to appreciate. When it was realized that the ribs were secured at the ends only on rollers or rockers, it would be felt that they should be well tied together at the top, and when the headroom was available it was a simple matter to put in the overhead bracing. The cost also was very little; it worked out at only 1·6 per cent. of the cost of the superstructure of the bridge.

So far as he was aware, there had been no trouble with the hangers. He did not see the last bridge finished, but he had examined the upper and lower ends of the hangers at the Alipore and Chitpore bridges before leaving Calcutta 2 years ago and had seen no signs of cracking. The concrete was only a protection for the steel, and it would not necessarily have been serious if there had been cracking; it would always be possible to cut out and replace any concrete affected. A very wet mix had been used for the hangers, as it was important that there should be complete adhesion to the steel.

He had expected difficulty in driving piles at an angle of 23 degrees, but they went in quite well and truly at the correct slope. He had been much relieved at that result, because the operation seemed to be rather difficult with the labour and plant available. The contractors were to be complimented on the way in which they had handled the job, seeing that such work had not been done before in Calcutta. Messrs. John King & Co. did the "Vibro" piling for the Narkeldanga bridge, and Messrs. Bird & Co. the pre-cast piling for the Manicktola and Beliaghatta bridges. The pre-cast piles had been very difficult to handle as some of them were 45 feet long, but all had been successfully driven without damage.

Mr. Temple asked about Franki piles. A bridge supported on Franki piles was being constructed when Mr. Atkins left Calcutta, and, though that bridge was a small one, he hoped that at some time a Paper on it would be presented to The Institution.

Mr. D. H. Remfry, in reply to Mr. Cook, observed that he did not think that the horizontal movement of the abutments had developed to any extent, except perhaps in the case of the Narkeldanga bridge. In the Dum Dum bridge, since its completion, the crown of the arch had dropped relatively to the abutments by 2⅛ inches in 11 years. Assuming that

there was no reduction in the length of the arch-rib, a drop of $2\frac{1}{8}$ inches at the crown was equivalent to a movement of 0·494 inch backwards of each abutment. However, part of the drop of the crown was probably due to the shrinkage of the concrete in hardening and maturing and to some plastic yield under load. Assuming that the abutments were immovable, a drop of $2\frac{1}{8}$ inches in the crown would correspond to a shrinkage of 0·474 inch in length of each half rib. That was a shrinkage of approximately 0·06 per cent. He did not think that such a shrinkage would have taken place in the last 11 years in the concrete itself. It was more likely that a shrinkage of 0·015 per cent. might have taken place, which would account for a drop of $\frac{1}{2}$ inch in the crown of the arch, and that the further drop of $1\frac{5}{8}$ inch in the crown of the arch was due to a horizontal movement of the abutments of about $\frac{3}{8}$ inch each. In the case of the Manicktola bridge, there was an observed drop in the crown of the arch of only $\frac{1}{2}$ inch. That, he thought, was accounted for by the shrinkage of the concrete in the last 7 years, and a shrinkage of 0·015 per cent. would account for that drop without there being any horizontal movement whatever of the abutments. The same remarks applied to the Beliaghatta bridge, where there was a drop of approximately $\frac{5}{8}$ inch in the crown, which was probably all due to shrinkage of the concrete. In the Narkeldanga bridge, however, there was a drop in the crown in 5 years of $2\frac{1}{2}$ inches, with no vertical settlement of the abutments themselves. It was very doubtful whether more than $\frac{1}{2}$ inch of that drop of the crown could be assigned to the shrinkage of the concrete, and probably 2 inches were due to horizontal movements of the abutments. If both abutments had moved equally, a movement of rather less than $\frac{1}{2}$ inch horizontally outwards of each abutment would account for that drop of the crown. In that case, however, it was probable that the main movement was in one abutment, namely, that which had a large main sewer passing close to but a short distance behind the thrust-plate, and it was quite likely that there might have been a horizontal movement of nearly 1 inch in that particular abutment and no movement at all of the other abutment. That was some indication of the value of the thrust-plates at the back of the abutment, as it was only in that case where the solidity of the roadway and embankment behind the abutment was uncertain and the earth there had been disturbed that any such horizontal movement had been observed.

With regard to overhead bracings, he did not altogether agree with Mr. Cook that they gave the bridges a somewhat clumsy appearance when looked at from the road. After all, appreciation of the design of a structure was a matter of education and of a feeling for fitness. He admitted that some of the bracings introduced might look heavy and clumsy to the general public, but that was owing to the public not appreciating the beauty which accompanied the fitness of any constructional feature for carrying out the job for which it was designed.

Mr. Cook had referred to the hypothetical side loading, which was

taken at per 4 cent. of the horizontal thrust in the rib; that loading was an assumption as to the force that tended to cause buckling of the rib laterally. Every long and slender rib had some tendency to buckle, irrespective of wind load. The buckling force would naturally be highest when the rib was most highly loaded, and that might not be when there was a heavy wind, because at times of storm and in hurricanes, bridges were generally not carrying any heavy loading. Mr. Remfry would say that the figure of 4 per cent. that he had taken as the load which tended to cause buckling was merely an assumed load. In the absence of any information to the contrary, he had allowed for such a load when designing arch-ribs. Very little had been written on the buckling tendency of slender arch-ribs, and he would be very much interested to have the views of members on that particular aspect of design.

In reply to Dr. Oscar Faber, he would explain that three out of the four three-hinged arches which crossed the Circular Canal were skew bridges, having a skew of 72 or 75 degrees. As the individual ribs of which those bridges were formed were 128 feet in span, only 3 feet wide, and had three hinges, they looked rather slender and it appeared desirable to insert ample cross-bracing. He was, however, inclined to agree with Dr. Faber that the bracing had been somewhat overdone in those bridges.

He agreed with Dr. Faber that bowstring girders were expensive in shuttering.

The Chitpore lock bridge had been made of the bowstring type because of the necessity of keeping ample head-room over the lock. The lock had to be worked to admit boats into the canal, and a certain space on either side of the lock was also necessary for that purpose. If girders had been adopted they would have been considerably deeper than the cross girders actually used, and, moreover, they would have required false-work below during erection. The centering of the arch-ribs had been well above the deck-system of the Chitpore bridge, and the shuttering for the cross girders had been supported from above so as to leave the maximum possible working space around the lock during the erection of the bridge.

With regard to the pile formula used, it was admitted that for the alluvial soil upon which Calcutta was founded it was not altogether satisfactory. The soil in Calcutta varied a good deal. In certain localities belts of a fairly good clay existed, but at the sites of the bridges under discussion no such clay had been discovered and the actual bearing resistance at the points of the piles was uncertain. If the points of the piles penetrated into a stratum like quicksand there would be no reliable bearing value, nor would there be consolidation which would assist. Although the formula used was not satisfactory in all respects, he thought it was not far wrong in regard to the supporting power of individual piles. It might be that it exaggerated the frictional resistance in certain cases and minimized the bearing power. It might well be imagined that the bearing power at the point of a pile should never be less than the pressure at that

level under the original superimposed loading of earth, and it was reasonable to expect it to be greater. In the formula taken, the bearing pressure was assumed to act over an area which was four times the sectional area of the pile.

There was little information available with regard to the supporting power of a group of piles. It was for that reason that the calculations in the Appendix had been given, in the hope that they would bring out anomalies, encourage discussion, and elicit the views of members. There had presumably been very considerable consolidation of the earth within the group of piles. Where conditions were worst, namely at the Dum Dum and Beliaghatta bridges, the outward flow of earth which might have occurred on driving a group of piles had been prevented by using sheet-piling. At the former bridge the sheet-piling surrounded the whole abutment on all sides, and at the latter sheet-piling had been driven along the front edge of the abutment in order to prevent any likelihood of the soil being displaced in the direction of the canal, in which direction it would be most likely to escape.

It had not been observed at any time that any layer existed which by its consolidation added considerably to the driving resistance of piles. In no case was there any sign of the piles reaching a gravel bed or a stiff clay stratum which would consolidate and give really good bearing resistance. Undoubtedly there was consolidation of the whole block engaged by the piles below the raft, and that resulted in the very satisfactory foundations which were finally obtained, the vertical settlements being small, except in the case of the Dum Dum bridge. At the Dum Dum bridge the conditions were very adversely influenced by having to take out old foundations which penetrated deeply below the bottom of the new foundation-raft. Those operations turned the soil just below the raft into a quagmire which made conditions most unpromising.

In reply to Mr. Walton, the maximum stress in the concrete in the arch-ribs of the canal bridges was 765 lb. per square inch, and in the deck-slab and cross beams the maximum working stress was 600 lb. per square inch. It was a matter of judgement to decide what stresses should be allowed, and the decision depended very much upon the skill of the labour employed. It was necessary at first to be conservative in deciding the working stresses to be adopted when dealing with a new material and under new conditions of site and labour-supply. Looking back on the results and the experience obtained in the course of the last 15 years, it did not appear that the stresses were too conservative, and he did not yet think that he would have been justified in using higher stresses at the commencement of the programme with inexperienced labour. In the first arch-ribs built for the canal bridges the intention had been not to exceed 800 lb. per square inch, and actually the maximum stress in the arch-ribs was 765 lb. per square inch. Those stresses had been raised to 985 lb. per square inch in the Tollygunge bridge.

He would not describe the concrete in the arch-ribs as hooped concrete. *Fig. 6* (p. 109) showed the construction of the ribs of the arch-bridges, and *Fig. 16* (p. 117) showed the construction of the rib of the Tollygunge bridge. Although not hooped in the accepted sense, the stirrups and lateral bindings, which were in sets spaced from 8 to 9 inches apart, possessed many of the beneficial attributes of hooping, as far as arched ribs were concerned, in that the spreading of the concrete under compression was most effectively resisted. It should further be remembered by Mr. Walton that the cement now available was better than that available 15 years ago, so that somewhat higher stresses could now be safely used. He did not think that hollow ribs or dumb-bell shaped ribs were suitable for spans of 150 feet and less.

He agreed with Mr. Walton that the concreting of the tie-beams involved a very interesting problem. One of the last parts of the bowstring bridges to be completed was the part at each end of the tie-beams adjacent to the springing of the arch.

In reply to Mr. Buckton, he would explain that the bowstring bridges were generally designed to take lower loadings than the canal bridges. The Alipore and Tollygunge bridges were on roads which served residential quarters. It was difficult to make a complete comparison of the relative costs of the three-hinged arch and the bowstring type, because the price of cement and materials had fallen somewhat during the period, whilst for the later bridges the competition in tendering had been distinctly keener.

The possibility of uneven settlement of the foundations of the arch bridges had been very carefully investigated, and all necessary precautions had been taken. The abutment had been made of a cellular formation with numerous cross walls which were 5 feet, 10 feet, and 13 feet deep, whilst the face wall of the abutment, having a depth of 26 feet, strengthened the abutment very greatly in a transverse direction. It was not likely that the raft could break its back due to uneven settlement, and no sign of uneven settlement had appeared.

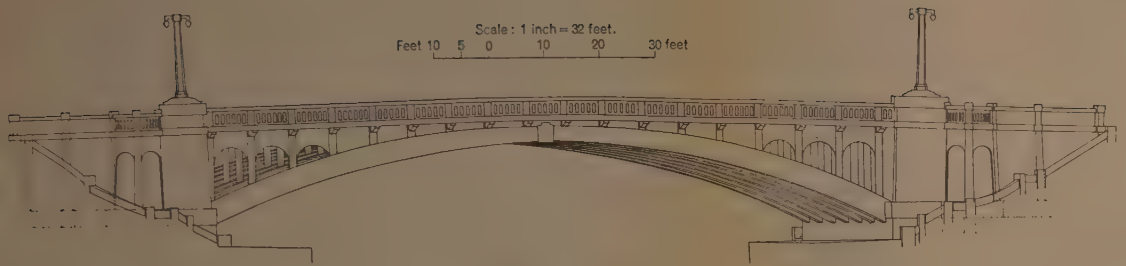
With regard to overhead bracings, none of the bowstring bridges was on the skew. Overhead bracings of skew bridges would be difficult to deal with and to make sightly at the same time.

For bowstring bridges generally, overhead bracings undoubtedly made the structure as a whole much sounder and more monolithic. As used on such bridges, bracings were very stiff and were not in the shape of straight horizontal transverse rectangular struts, as had sometimes been used. The provision of overhead bracings was much more important in Calcutta and in some parts of India than it was in England. Calcutta was subject to moderately severe earthquakes, and in his own time in India he had seen Calcutta Cathedral lose its spire twice.

*** The Correspondence on the foregoing Paper will be published in the Institution Journal for October, 1938.—SEC. INST. C.E.

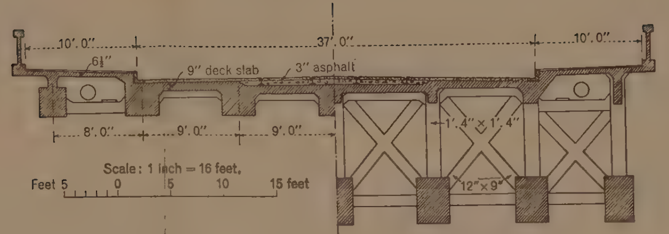
THE RECONSTRUCTION OF MAIN ROAD BRIDGES, CAL

FIG: 1.



GENERAL ELEVATION.

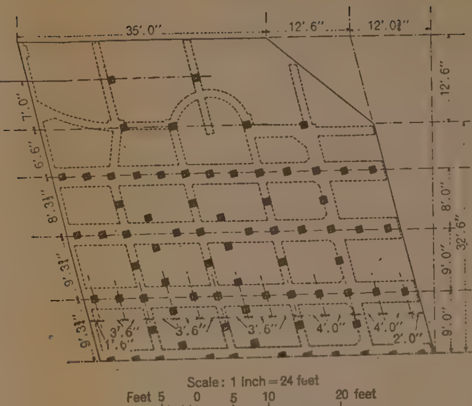
FIGS: 3.



HALF CROSS SECTION NEAR CENTRE.

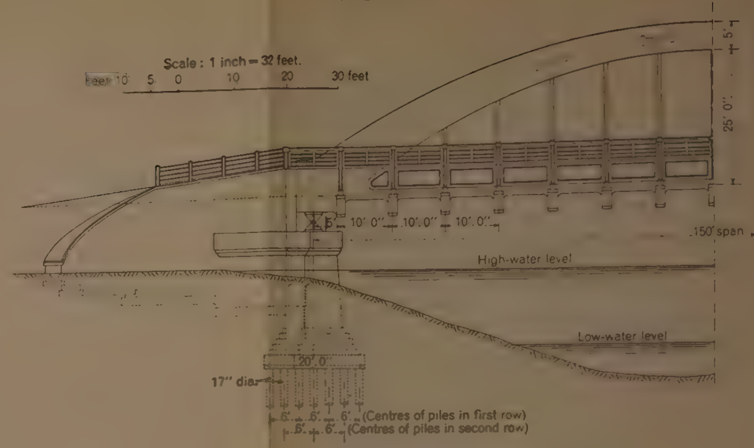
HALF CROSS SECTION NEAR ABUTMENT.

FIG: 4.

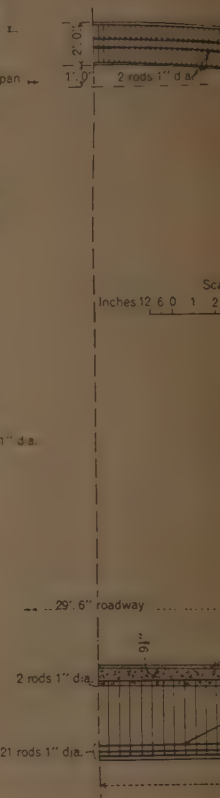


HALF PLAN OF ABUTMENT.

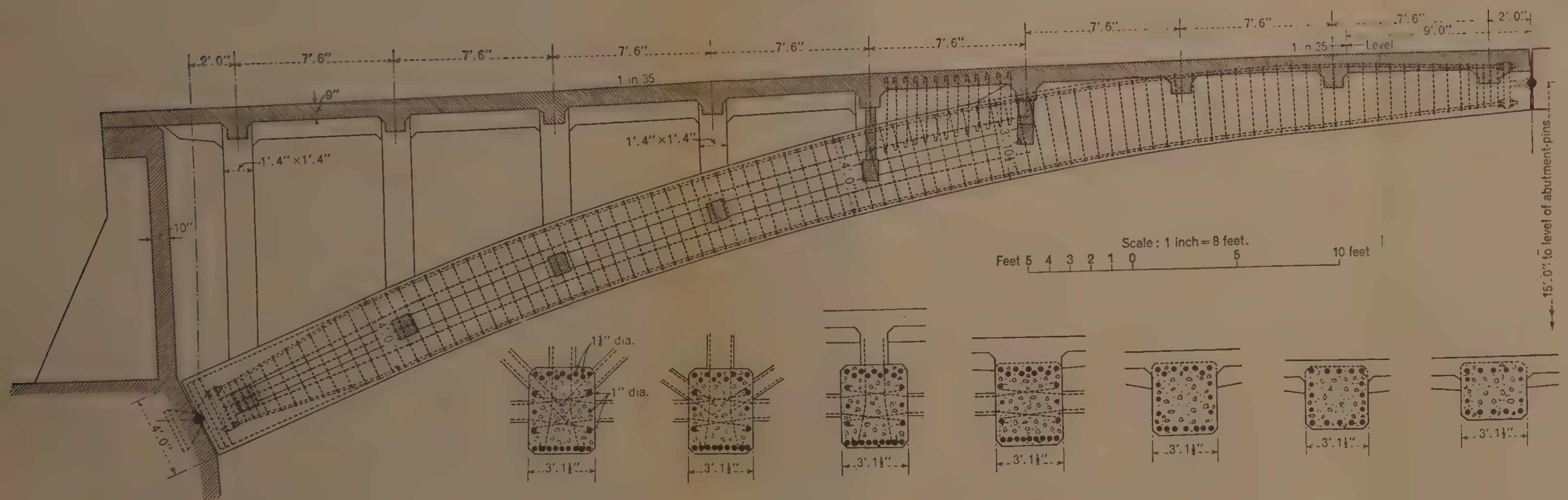
FIG: 8.



GENERAL ELEVATION

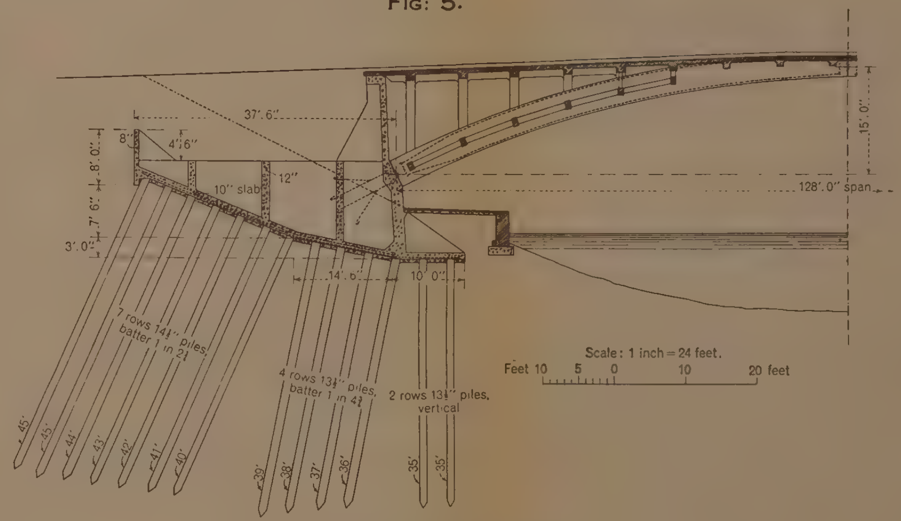


FIGS: 2.



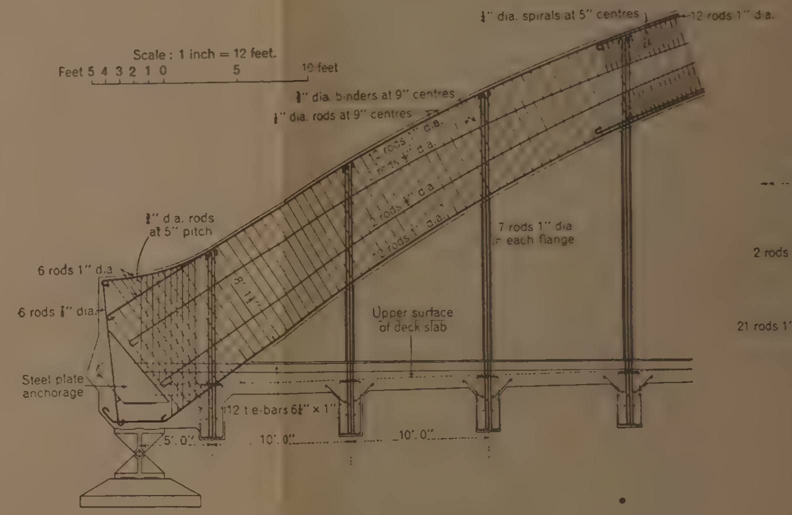
LONGITUDINAL SECTION OF RIB.

FIG: 5.



LONGITUDINAL SECTION OF ABUTMENT

FIG: 10.



LONGITUDINAL SECTION OF RIB.

ARCH BRIDGE.

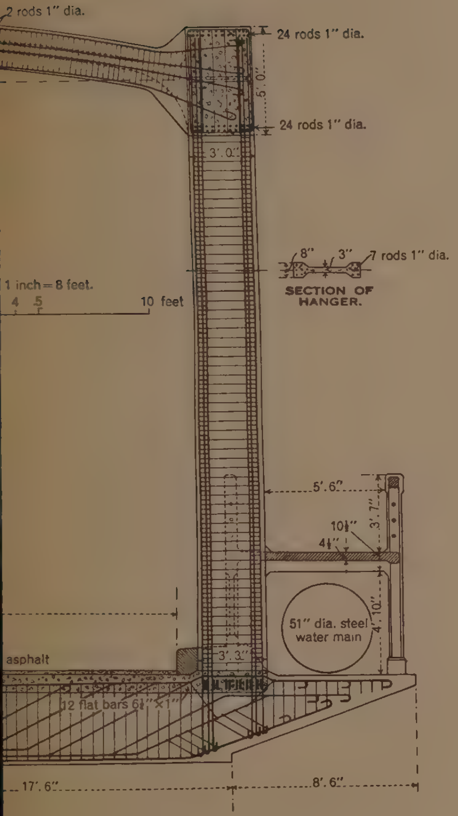
ALIPORE BRIDGE.

The Institution of Civil Engineers. Journal. June, 1938

WILLIAM CLOWES & SONS, LIMITED, LONDON.

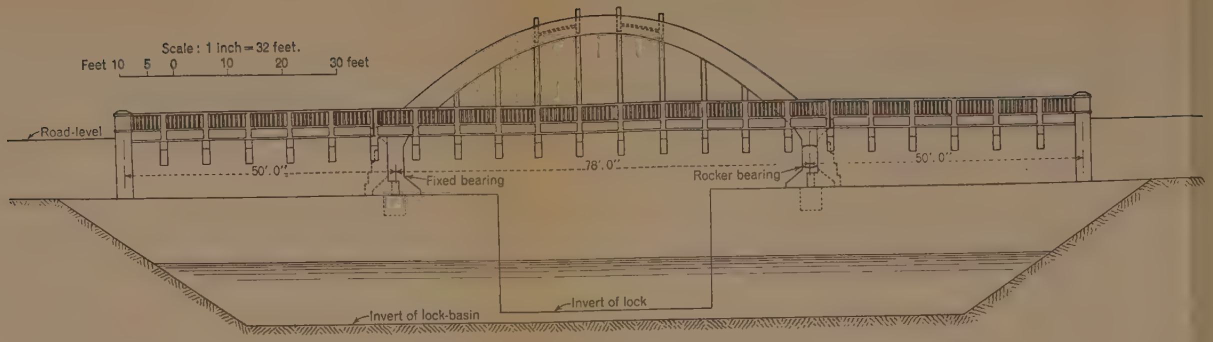
UTTA.

FIG: 9.



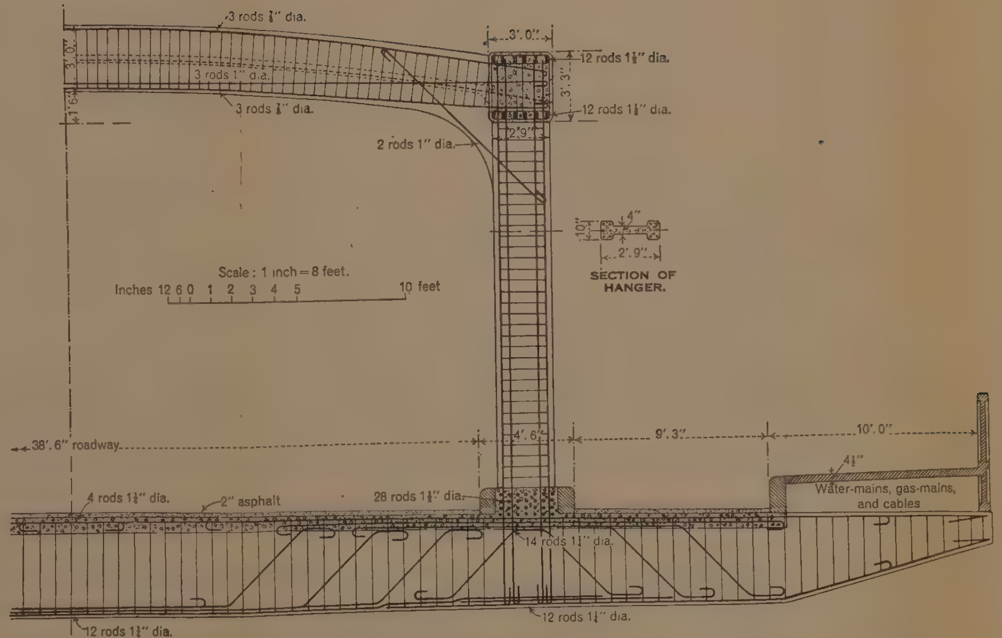
CROSS SECTION.

FIG: 11.



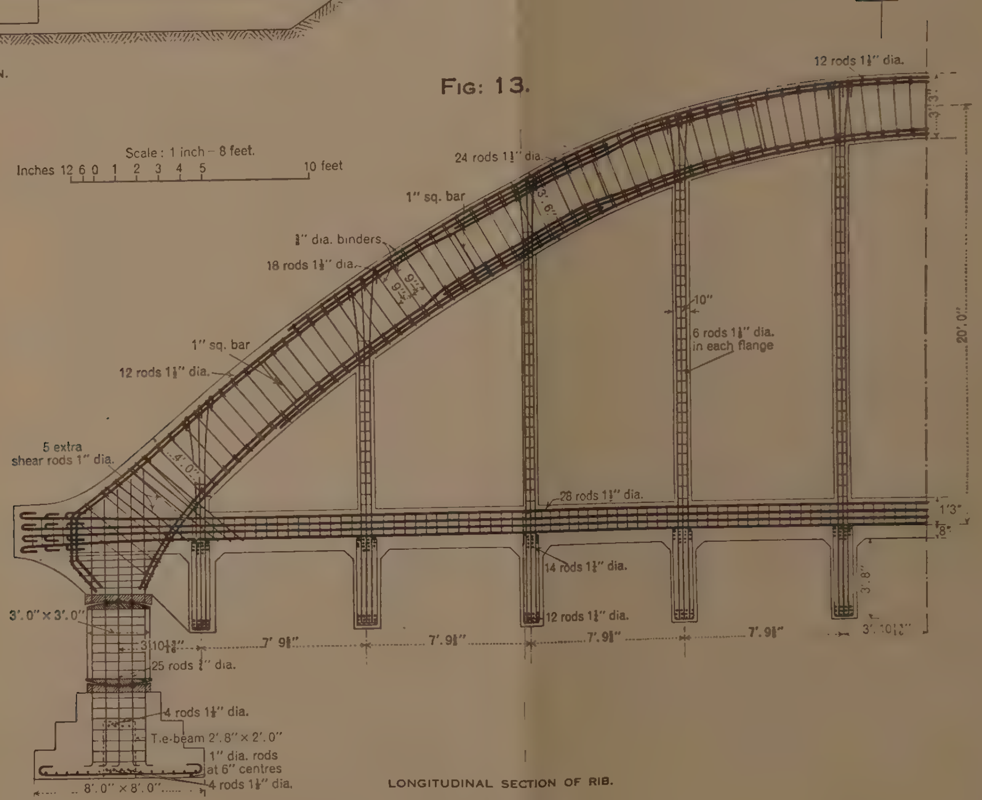
GENERAL ELEVATION.

FIG: 12.



CROSS SECTION.

FIG: 13.



LONGITUDINAL SECTION OF RIB.

CHITPORE BRIDGE.

M. R. ATKINS and D. H. REMFRY.

ORDINARY MEETING.

5 April, 1938.

WILLIAM JAMES EAMES BINNIE, M.A., Vice-President, in the Chair.

The Council reported that the following had been duly elected as.

Members.

JOHN HOPE BLACKETT.
CHARLES AUGUSTUS CARLOW.
JOHN LEONARD EVE.

Associate Members.

DAVID RICHARD BEVAN, Stud. Inst. C.E.
LEOPOLD BROOK, B.Sc. (Eng.) (*Lond.*), Stud. Inst. C.E.
JAMES FRANCIS BURFORD, B.A. (*Cantab.*), Stud. Inst. C.E.
WALTER HAROLD WISHART CANE, B.A. (*Cantab.*), Stud. Inst. C.E.
THOMAS HERBERT CANNING, Stud. Inst. C.E.
VINCENT HARVEY COLLINGRIDGE, Stud. Inst. C.E.
THOMAS ARTHUR JOHN DICKENS, B.Sc. (*New Zealand*).
HAROLD JOHN EDDIE.
EDWARD WALWYN GOLDSTRAW, B.Eng. (*Liverpool*), Stud. Inst. C.E.
ROBERT GRIEVE, Stud. Inst. C.E.
HENRY ALFRED LEADER, Stud. Inst. C.E.
EDWIN HENRY LOVATT, B.Sc. (*New Zealand*), Stud. Inst. C.E.
JOSEPH PICKERING OGDEN, Stud. Inst. C.E.
HAROLD ORMISTON, B.Sc. (*Leeds*), Stud. Inst. C.E.
DONALD PARKER, B.Sc. (*Birmingham*), Stud. Inst. C.E.
EDWARD GEORGE PIKE, Stud. Inst. C.E.
JOHN PHILIP RIDD, B.Sc. (Eng.) (*Lond.*), Stud. Inst. C.E.
JACK RIGG, Stud. Inst. C.E.
EDWARD THOMAS RUSSELL, B.Sc. (*Edin.*), Stud. Inst. C.E.
ERWIN HENRY MARTIN SLADE, B.Sc. (Eng.) (*Lond.*), Stud. Inst. C.E.
ERNEST HENRY JAMES STEWART, B.Sc. (Eng.) (*Lond.*).
JAMES HARVIE STRANG.
ARTHUR ERIC SUMNER, B.A. (*Cantab.*), Stud. Inst. C.E.
EDMOND STANDISH WALLER, M.C., B.A., B.A.I. (*Dubl.*).
SYDNEY WOOD, Stud. Inst. C.E.

Associates.

FREDERICK CUTHBERT PELHAM LAWRENCE.
ARTHUR EDGAR TYDEMAN.

The following Paper was presented for discussion, and, on the motion of the Chairman, the thanks of The Institution were accorded to the Author.

Paper No. 5173.

"The Work of the Paint Research Laboratory of the London, Midland and Scottish Railway Company." † *

By FRANK FANCUTT, F.I.C., A.M.I. Chem. E.

TABLE OF CONTENTS.

INTRODUCTION.

THE opening by the late Lord Rutherford of the London, Midland and Scottish Railway Company's Research Laboratories at Derby, in 1935, was the culminating point in a series of developments which had their origin more than 70 years before in the opening at Crewe, in 1864, of the first of the Chemical Laboratories. The other Companies, which in the grouping of the railways in 1923 combined to form the L.M.S. Railway Co., soon followed the lead thus given by Crewe, and at the end of the nineteenth century all the railways were equipped with some form of chemical testing laboratory. Although there was a certain amount of reorganization following the amalgamation, the various chemical laboratories continued to function independently, under departmental control. Each laboratory tested the whole range of the miscellany of articles which are consumed or manufactured by a railway company. In 1928, however, Sir Josiah Stamp set up a committee to consider the need for a more extensive research organization, and following this committee's findings Sir Harold Hartley was appointed Vice-President and Director of Research, and an Advisory

† Correspondence on this Paper can be accepted until the 1st September, 1938.—SEC. INST. C.E.

* Reference may also be made to the following Papers, which may be seen in the Institution Library:—

No. 5111, "Painting as it Affects a Railway Engineer," by Frank Fancutt.

No. 5112, "The Engineer and the Paint Technologist," by F. G. Dunkley and Frank Fancutt.

Committee comprised of a number of distinguished scientists and the chief technical officers of the Company was set up.

In 1931, Sir Henry Fowler, M. Inst. C.E., was given charge of the Chemical, Paint, and Mechanical Testing Laboratories. In the interval between the grouping of the railways and 1931 the various chemical laboratories had begun to specialize in various aspects of the Company's work, and, in particular, the Chemical Laboratory at Wolverton had begun to specialize in the study of paints and varnishes. This development took place so rapidly that the laboratory had by 1930 become known as the Paint and Varnish Laboratory. The setting up of a laboratory specially devoted to the solution of painting problems and to the control of the Company's paint purchases indicates the importance which had come to be placed on this hitherto neglected problem.

When Sir Henry Fowler retired in 1932, the Chemical, Paint, Metallurgical, and Engineering Laboratories were grouped together into an independent Research Department under a Research Manager. The provision of a building to house the new Department was a logical development, and now the various sections are grouped together in the new laboratories at Derby, with the main exception of the chemical laboratories, which are still located at the Company's main works. The fullest degree of co-operation is maintained between the various sections, but much of the work is well defined, and is best completed within the section covering the particular field into which the work falls.

The centralization of the Research Department in the new laboratories at Derby has increased the effectiveness of the various sections, but its activities do not represent the whole of the Company's interest in scientific research. The L.M.S. Railway Co. is a member of six Research Associations, and the closest co-operation with the Department of Scientific and Industrial Research is also maintained. Thus the research policy is thoroughly comprehensive and designed to help the Company to give better service to the public at the lowest cost compatible with the public interest.

The three main ways in which research work originates are (1) as the result of the recommendations of the Advisory Committee, (2) at the suggestion of the Research Department, and (3) as a result of action on the part of the chief officers of the Company. The larger problems are in any case first discussed by the Advisory Committee, who lay down the general method of approach. All other researches are authorized by the Director of Research or the Research Manager. The Advisory Committee may decide that a problem is one more suited to be undertaken by one of the outside Institutions, and may recommend that such a course should be taken.

Sufficient has now been said of the history, scope, and general principles of direction to form a background against which a brief sketch of the work conducted in the Paint Section of the Research Department of the L.M.S. Railway can be painted.

In order to bring out the magnitude of the painting problems of the L.M.S. Railway, the following figures may be quoted. The Company possesses 2,395 passenger stations and halts, 8,000 locomotives, 24,000 coaching vehicles, 270,000 merchandise wagons, 20,000 road vehicles, 45 steamers, 31 hotels, and 6,941 route miles of track with their bridges and signalling equipment, etc. The amount spent on painting is in excess of £500,000 annually, but the value of the property protected exceeds this amount many times (the Company's capital is £439,000,000). The number of men engaged in painting at one depot alone is 400.

There is probably no other single material used by the railway which can play so great a part in maintaining the Company's property in a sound and attractive condition, and in waging its defensive warfare on land and sea, against the assaults of corrosion and ravages of decay. Whilst the value of paint as a protective coating is the prime consideration, the appearance of the Company's property has a definite psychological value.

Description of Laboratory Organization.

Work in the Paint Laboratory is done on behalf of every department of the Company in one form or another, for, in addition to paint, other materials are dealt with, such as cleaning materials and various protecting compositions for wood and metal. There is a right and wrong way in which to apply paint to a given job, and each type of material must be submitted to an appropriate examination to ensure its suitability for the work on which it is to be used. As is the case with other Laboratories on the L.M.S. Railway, routine testing and research work are as far as possible treated as separate branches of the work, but one must of necessity be complementary to the other, and in practice it is difficult to decide where routine work ends and research work begins. The general organization of the staff of the Paint Laboratory is a problem which has been largely solved by the division of the work into three sections, each working under a sectional head who, by his intimate knowledge, is able to regulate the work in its passage through the Laboratory, and to advise on any aspect of the problem with which the section deals. Within the sections the movement of staff is adjusted to suit the irregularity of the incoming work, but owing to the different qualifications required by the staff of the individual sections the interchange of staff between sections is rare.

The main section is concerned with the routine testing and control of supplies, and, in addition, the problems relating to the development and manufacture of cleaning solutions are dealt with. Supplementary to this section is that concerned with the development of new processes, problems concerned with application, the control of trials, the investigation of abnormal failures, and any special application problems. Finally there is the research section, which concentrates on the solution of unusual problems, and of the development of new materials and methods

f test, particularly those having some bearing on the actual performance f paints and kindred materials.

An efficient library service is maintained by the Research Department, nd most standard works of reference, in addition to eight trade and scienti- c journals dealing with painting matters, are available on the premises. lmost any book is obtainable on loan at very short notice, and the library ervice plays no small part in the efficiency of the Laboratories.

Mutual problems are frequently discussed with outside research stations, nd whilst it has been found that their angle of approach is in general ifferent from that made necessary by the Company's interests, there emains a wide field common to both points of view, and the exchange of leas has proved helpful to both parties. Co-operation with the paint ndustry has led to developments which may prove to have far-reaching ffects, so far as new materials are concerned, and it is proposed to mention ater some instances where significant progress has been made. Another spect of the Company's endeavour to foster happy relations with the trade s that full facilities are readily extended to any firm receiving a criticism f one of its products to visit the laboratory to witness the actual conditions f test, and to discuss possible ways of overcoming the difficulties ex- erienced.

The Paint Technologist represents the Railway Companies of Great Britain on a number of committees of the British Standards Institution. These committees have almost reached the end of their task of revising the whole of the specifications for ready-mixed paints, varnishes, and pigments. He also serves on the Sub-Committee for Protective Coatings of the Corro- ion Committee of the Iron and Steel Institute, whose work promises to lear away much of the confusion and misunderstandings which prevail mongst the users of iron and steel as to the correct methods of combating orrosion by paint and other protective coatings.

Control of Paint Supplies.

dvantages of Specifications.

The problem of the control of paint supplies is a complex one, involving he co-operation of the Paint Laboratory, the using departments and the tores Department. The number of paint manufacturers and the variety f their products make it essential for a large purchaser such as the L.M.S. Railway to purchase its requirements to specifications, in order to provide basis for strictly competitive quotations throughout the system. The rimary requirement in the application of this method of purchasing is hat the specifications should be sound, and that they should be recognised s such by the trade. The drafting of such specifications is the responsi- ility of the Paint Laboratory, after which they are formally approved by he using and Stores Departments for issue.

It is by no means uncommon to find that manufacturers adopt these

specifications as a working basis for their own standards, and this applies also to contractors building stock for the L.M.S. Railway, who also adopt the schedules setting out the sequence of operations as their working basis for their own painting.

Materials purchased from a new supplier or to a new specification are specially examined and watched for a period in service, and quarterly reports are prepared on these paints which have run under service conditions in order that all their properties may be evaluated. The routine checking of standard supplies from approved manufacturers is a relatively rapid procedure, and a report is usually made within a week of the receipt of the sample representative of the bulk supply. There is no doubt that the practice of purchasing to specification, provided such specifications are mutually reasonable, has resulted in considerable financial advantage to the Company and has facilitated standarization of practice. Actual savings in the price of paint materials yield a total considerably in excess of the annual expenditure on the Paint Laboratory.

When specifications have been drawn up to cover the quality of the separate ingredients used in the paint and the proportions have been standardized, the authorized formula is put into operation in the works and watched from time to time in order to ensure that the composition is being adhered to and that the working properties of the paint are satisfactory under the somewhat varying conditions which occur according to the location of the works. The procedure followed after a formula is issued to the works calls for spot testing whereby a paint, after being mixed and issued to the painter, is taken from his pot and checked in order to see that no dilution or alteration of the formula has occurred after it has left the colour-mixing room. This is most important if the expected life is to be realized, since the thinning of paints can deprive the film of a certain amount of durability. It will thus be seen that it is not sufficient to prepare specifications and schedules and to leave them to the works contro without ensuring that the accepted standards are actually being applied in practice.

Acceptance-Tests and Works-Control.

Before proceeding to describe the tests in detail it would not be out of place to consider what are the essential features of the composition of paint. An ordinary paint is a complex containing :—

(1) A drying oil, such as linseed oil, which on exposure dries to a gelatinous substance forming a more or less impervious film over the surface.

(2) A pigment, which not only provides the colour and gives the property of opacity to the paint, but also imparts certain other physical and chemical properties to the film.

(3) A drier, which is an oxide or salt of a metal exhibiting differen

stages of oxidation, generally lead, manganese, or cobalt, or more often mixtures of these. The drier catalyses the drying process of the oil.

(4) A thinner, such as turpentine, the chief function of which is to permit the easy application of the paint.

The general practice to-day is to base paint-specifications on considerations of the paint's chemical composition; although such a practice has in the past worked quite satisfactorily, modern developments in paint-manufacture have so increased the range of raw materials that the possibility of an alternative basis for specifications is being explored.

Returning, however, to a consideration of the present tests and methods of control, the various components of the paint are all controlled by specifications both as to quality and quantity (for the ratio of each ingredient to the others is important). The thinners, the oil, and the pigment are all estimated, and their quality individually tested. Certain properties of the paint are ill-defined, and are controlled by reference to a standard pattern. Such properties are :—

(1) Opacity, or the power of the paint to obliterate the surface to which it is applied.

(2) Spreading rate, or the measure of the time required to cover a given area. This property is difficult to define without reference to a standard pattern, because there are a large number of factors outside the paint which can influence the result, and the condition of the test is that the standard pattern must be tested under the same conditions at the same time and the results compared.

(3) Covering power, or the amount of paint required to cover a given area. This property, too, has widely differing values for the same paint under different conditions, and the conditions of test are the same as those for the previous test.

(4) Consistency, or stoutness. This is an important property, and a machine is being designed to measure it accurately.

(5) Ease of application. The difficulties of defining this property in ergs or other scientific units are self-evident.

(6) Gloss. There are now devices available for comparison and measurement of gloss, but for most purposes only those differences which can readily be detected by the eye are of importance in paints, etc.

(7) Flow, or the power of a paint to assume a uniform appearance free from brush-marks. Obviously the best method of testing this property is to brush out the paint and compare the result with an agreed standard.

(8) Colour. Only those who have had experience of comparing colours will appreciate the difficulties associated with it.

Instruments are available for measuring colour in terms of the three primaries, but those which are efficient are too costly for use in routine testing.

(9) Fastness of colour to light. This property is determined by the exposure of the sample to ultra-violet light. As the emission of active rays from the carbon-arc lamps used varies slightly, the test is made comparative by the simultaneous exposure of a standard sample which is known to be satisfactory in this respect.

Many other properties are also determined and include the determination of the weight per gallon, which serves as a ready check on formulation. The fineness of all paints, except those containing flake pigments such as aluminium, graphite, and micaceous iron, is such that all particles are required to pass completely a standard 200-mesh Institute of Mining and Metallurgy screen. The drying time is also closely watched, and is required to fall within narrow limits, since, generally speaking but with some important exceptions, the quicker the drying the less durable is the paint. Practical considerations have, however, to be taken into account, and the specification limits are designed with both points in mind. Specific tests are conducted on such properties as resistance to acids in connexion with paints to be used on stations and with varnishes, etc., which are likely to be washed with acid cleaning-solutions. Tests for resistance to alkalies, cleaning or burning oil, or any other active agent are included where required. Certain types of finishes, notably varnish and enamel, are also tested in respect of elasticity, adhesion, and hardness. Thus the interests of the using departments are safeguarded to the fullest extent, and only those materials which are suitable for a particular purpose are recommended for use.

In addition to the testing of current supplies purchased to specifications, which forms the greater part of its work, the Routine Section is also responsible for the testing and evaluation of proprietary paints, which are examined from time to time at the request of the chief officers of the Company, including the Chief Stores Superintendent, for the determination of the chemical composition and for such performance and special tests as are appropriate to the particular paint, and, in addition, for investigating any claim which is specifically mentioned.

Chemical versus Physical Testing.

Paint should be possessed of the requisite adhesion, have the necessary strength to stand up to traffic conditions and abrasions, and, in addition, be impervious to moisture. These properties cannot be determined by chemical means. It has, therefore, become necessary to study the physical properties of films in order to safeguard these interests. The adhesion and film-strength is taken care of by such instruments as the tensile-

trength and percentage-elongation machine, the hardness by various types of apparatus which will measure hardness in relation to standard abrasives, and the flowing properties by the Plastometer and the Hoppler Viscometer. These tests are now being rapidly developed, but the main difficulty is concerned with the method of producing films; it has been found that the one giving most consistent results is to spin paints of regulated viscosity on a turntable revolving at a constant speed. Paint is applied to a tin plate coated with mercury to form an amalgam surface, and by this means it is possible, when the film has become dry, to detach it without difficulty. Measurements are then taken by means of the vibrating reed spherometer to ensure that the actual test pieces are of consistent film thickness.

The following facts are of interest :—(1) A varnish film is of the order of $\frac{1}{500}$ inch thick, and is capable, even after 3 or 4 months' ageing, of stretching to double its original length ; (2) Synthetic resin varnishes have very much higher tensile strengths than ordinary fossil-gum varnishes, and cellulose lacquer films are even stronger ; (3) It requires 800 grams of coarse carborundum powder falling through 6 feet to wear away a cellulose lacquer film $\frac{1}{1000}$ inch thick.

In addition to the work on physical testing, an investigation is proceeding with respect to accelerated weathering. The accelerated-weathering machine which has been installed in the Laboratory for 5 years consists of two carbon-arc lamps, which are suspended at the end of two arms which slowly revolve horizontally in a tank of 5 feet diameter. At right angles to the arms carrying the arcs are two water sprays, which also rotate. On a rack round the inside of the tank are stood steel panels which are painted with the samples under test. The paints are thus exposed to ultra-violet light, and, at will, to water sprays, which simulate the sun and rain respectively. Approximately 5 weeks in this machine are equivalent to 12 months of normal weathering. The panels are exposed to light alone, light and water, and water alone, in a predetermined cycle. The effect of frost is obtained by placing the panels in a refrigerator at intervals, and the effects of various types of polluted atmospheres are reproduced by placing the panels in glass tanks into which the corrosive element has been introduced as a very fine mist. The type of breakdown obtained in the accelerated-weathering tests resembles very closely the type of breakdown experienced in service, but further experimental work is needed before implicit trust can be placed in the results. The possibility of designing a compound machine capable of imposing all these tests on the specimen automatically is now being considered, and it will be readily appreciated that the system of paint-control would be radically altered if the use of such a machine, in conjunction with the determination of physical properties, were to make it possible completely to evaluate a paint in a few weeks.

It may be of interest to note that much of the apparatus used for the determination of these physical properties of paint films is being made

in the laboratory workshop, since none of the apparatus at present available is generally adaptable to the problem. This is particularly instanced in the case of a constant-speed mandrel apparatus, and it may be said that this is the only apparatus of its type at present available.

Advantage of the experience gained by physical testing has already found outlet in the specifications controlling the purchase of and supplies of synthetic resin enamels for signal arms and synthetic resin clear varnish for finishing locomotives and carriages.

The Development of Paints.

Oil Paints.

From the definition of paint given earlier it will be recalled that a paint consists of a mixture of pigment and drying oil, thinned with a volatile solvent, to which is added a drier to speed up the hardening or drying of the paint. The drying oils are either of vegetable or animal origin. The one mainly used is linseed oil, which is expressed from the seed, refined, and treated in various ways to produce different grades of oil for particular purposes; the best linseed oil comes from the Baltic. Exposed to air, linseed oil takes up oxygen, and forms a compound—linoxyn—which is an elastic solid. The process of oxidation does not cease when the paint becomes dry but continues, and, as a result, the elastic film first formed becomes progressively harder until it is brittle, and ultimately disintegrates. The compound "linoxyn" (a generic name given to the product of all drying oils on oxidation) is insoluble in all the common constituents of paint, a fact of the utmost importance, for upon it depends the ability to apply subsequent coatings without disturbing the dry film. Very thin films of paint are permeable, and, in order to obtain an impermeable film, a number of coats must be successively applied, the permeability decreasing with the increase of film thickness.

Many oils have the property of forming an elastic coherent film on drying, and among them is tung or China wood oil, a product of China and recently of the United States of America and the Empire; it is being increasingly used, giving a film less permeable than linseed oil, but, unless carefully and specially treated, not so durable. Oiticica, perilla, and soya bean oils are finding increasing use. In addition to these, fish oils are also used, but they are semi-drying oils, and their addition in large quantities to any paint slows up the drying considerably.

A drier is a metallic oxide or salt which, dissolved in the oil, acts as a carrier of oxygen. The metal takes up oxygen, forming an unstable compound which breaks down and passes on the oxygen to the oil, the cycle being repeated. Very small quantities of these metallic salts are sufficient to catalyse the drying of large quantities of oil. It is usual to use the metallic salts of two different metals, lead and manganese being a frequent combination. When the drier is added to the heated linseed oil, the product

is known as boiled linseed oil. Another form of linseed oil is stand oil, the manufacture of which was originally a Dutch process and consisted of heating the oil alone without driers. The oil was thickened considerably and its properties much improved; it was still slow drying, but gave a much more glossy film, had remarkable ability to flow out under the brush, and was the basis of enamels.

The addition of driers to a paint is critical, as an excess will prevent the paint from drying and will cause cracking of the paint film. In addition to the incorporation of driers in boiled linseed oil, terebine (liquid) driers or patent (paste) driers are often added to paints. The first of the two forms is a dilute solution of the metallic salts in white spirit, and the second is in paste form, usually ground in linseed oil, with barytes as an extender or diluent. Great care should be exercised in their use, and they should never be added to a proprietary paint, since by them the properties of the paint may be entirely changed.

Classification of pigments is difficult, since they fall into no clearly defined classes except that of colour, and it is usual to use this somewhat arbitrary system of classification, in which the group of white pigments is the most important, since white paints, and nearly all light-coloured paints, contain them. The chief members are white lead, zinc oxide, lithopone, and titanium oxide pigments.

White lead is itself a product of corrosion, and until the last few years there was only one method of manufacture that gave a pigment which combined a sufficient number of desirable properties; this was the old Dutch stack process which consists of exposing lead to the fumes of acetic acid, fermented by spent tan; the newer "chamber" process is a variation of this. White lead was indisputably the best white pigment available until recent years. The peculiar "feel" of paint made from it under the brush is due to a reaction between the oil and the white lead, which results in the formation of lead soaps, and to which fact the durability of such paint is attributed.

White lead has several disadvantages; it is readily acted upon by industrial atmospheres generally, and especially when sulphuretted hydrogen is present, which results in the formation of a black compound—lead sulphide—and the blackening of the paint film. Wherever salt water spray comes into contact with it action quickly ensues, resulting in the complete destruction of the paint. The film of white lead paint is soft, and so is liable to physical damage; it is also very prone to collect dirt, and has a tendency to "chalk." "Chalking" is the name given to that property of paints which results in surface-disintegration, and gives rise to the presence of a powder on the painted surface which can be easily wiped off. The presence of chalking is indicated when streaks of colour are found as a result of rain carrying the powder over adjacent surfaces.

Zinc oxide is a pigment of great importance, and one which is largely used in spray paints. It is prepared by heating either the metal itself or

spelter to a temperature slightly above its boiling point, when it volatilizes and forms zinc oxide which solidifies, and is suitably collected. Zinc oxide is remarkable for its brilliance of colour, but its opacity is slightly less than that of white lead. It is non-toxic, and is not discoloured by industrial atmospheres, the sulphide of zinc being a white pigment of some value. It forms paints of good durability, and of higher gloss than those containing white lead. The brush-marks are not so pronounced as with lead paints, and the film is harder and less liable to retain dirt. It was the introduction of zinc oxide which made white enamels possible, with their hard, glossy, smooth, and durable films. Leaded zinc-oxide paints combine to some extent the properties of the lead and the zinc-oxide paints, and have excellent durability. Lithopone is a zinc-containing pigment; it has a white colour, and is of exceptional opacity but of poor durability, and not recommended for exterior use.

Titanium white is a new pigment of considerable value, particularly as regards opacity; its use has made "one coat" enamels and paints a feature of modern paint technology. It is a particularly inert pigment, and invaluable where it is necessary to obliterate the surface to which it is applied.

Oxide of iron pigments give paints of very good durability and films possessing a high degree of impermeability. Among the natural oxides, the Spanish-mined material is superior. Among artificial oxides the best oxide comes from copperas or green vitriol, which is roasted in furnaces; the resultant oxide is an excellent pigment.

Red lead is an oxidation-product of lead, resulting from the careful heating of the metal in air. Ground in linseed oil it acts as a drier, and paint made up with it quickly becomes hard. Red lead paints are rarely used for decorative purposes, because they are difficult to apply and change colour fairly rapidly on exposure. The virtue of the pigment in priming paints appears to be due to the fact that it assists the formation of a protective film of oxide on the metal. There is no doubt that, whatever the explanation, red lead definitely has some rust-inhibitive action, a property shared by chromate pigments, such as lead chromate and zinc chromate.

Amongst black pigments only graphite is of sufficient interest to mention here. This is not intended to infer that graphite is the black pigment most used, but that it has a particular interest in connexion with the corrosion of metals. Thc main difference between graphite paints and other paints is that graphite is a conductor of electricity and is cathodic to iron and steel, and is therefore liable to promote corrosion. Mixed, however, with red lead and other extenders, a paint of excellent properties is obtained. The flakes of the graphite overlapping in the film result in a particularly impermeable coating.

Similar to graphite in appearance is micaceous iron ore. This pigment occurs as a mineral in many places and is finding an increasing use. The

use of micaceous-iron-ore paints is limited by reason of their dark grey colour, and by the fact that the film is particularly soft, and should not be used where it is liable to mechanical damage.

Metallic lead, aluminium, antimony, and zinc pigments are used in certain proprietary paints. The metal acts anodically to iron and steel, and so prevents its corrosion. Experiments have been conducted on zinc-dust paints, which have shown that even where small breaks, introduced accidentally in brushing or deliberately made, occur in the paint film, these paints prevent corrosion.

Large classes of pigments have been omitted since their function is purely that of imparting colour to the paint, and, interesting as a study of these pigments would be, space does not permit of more than this passing reference. From the little it has been possible to say in connexion with pigments it will be seen that few, if any, of them possess all the desired properties, and modern paints almost invariably contain mixtures of various pigments.

The volatile thinners commonly used are white spirit or petroleum distillate (a product obtained in the distillation of motor-spirit from petroleum oils), and turpentine which is obtained from the distillation of the gum exuding from pine trees during the life of the tree, or from the destructive distillation of the wood of the tree. Turpentine is a better solvent for the gums which are used in varnishes, and which are sometimes added to paints to give a better adhesion and decrease the permeability. It is also a solvent for the lead soaps which are formed in white-lead paints, and for this reason should be used alone or in conjunction with white spirit in such paints. In most other cases white spirit is quite equal to turpentine, and as turpentine costs three or four times as much, white spirit should be used wherever the considerations indicated do not apply. New solvents are on the market which are designed to meet special needs, and various advantages are claimed for them.

Synthetic Painting Materials, etc.

A word in explanation of the new synthetic resin paints of which most people will have heard, will be appropriate here. Natural fossilized resins or gums have long been used by the paint trade to add gloss to paints, to decrease their permeability, and to make them better able to withstand certain conditions. Unfortunately, the supplies of gums obtained through native sources are liable to adulteration and irregularities. Further, the gums, as mined, are not soluble in the usual constituents of paints, and require processing. This processing is the work of a skilful varnish-maker, and is known as "running," an operation which does not lend itself to scientific control. Great care is needed in its manipulation, during which a loss of 30 per cent. by weight of the gum is experienced. In these circumstances, certain synthetic materials, of known purity and of controllable physical properties, have been placed on the market. They

possess somewhat similar properties to natural gums and resins, but differ widely in chemical composition. The two types of synthetic resins in extensive use in paint manufacture are phenol-formaldehyde resins, and alkyd or glyptal resins. Sometimes the resins are combined with the fatty acid of a drying oil, and in this way paint-vehicles of exceptional properties are produced, which are chemically stable and represent the greatest advance in paint technology of recent years. These materials may be used as varnishes, or pigmented to make paints and enamels.

The advances in raw materials used in paint manufacture have been matched by technical advances in the mixing, grinding, and homogenizing machinery, making the gap between paints made by hand in a tub and those manufactured under closely controlled scientific methods in a modern paint-factory wider than ever before.

Numbered amongst the new products of the paint industry are sulphur-ized oil paints in which the chemical resemblance between oxygen and sulphur is utilized. Linseed or tung oil is acted upon by sulphur, and the resultant product emulsified in white spirit (in which the sulphurized oil is insoluble). Paint made from this medium can be applied in successive coats, "wet-on-wet," that is to say, without waiting for the paint to dry. Five or six coats can be applied in 1 day, and the whole film dries as a unit. The sulphur causes the gelatinization of the film normally brought about by oxidation. The paints are fairly durable, but appear to be somewhat lacking in adhesion.

Cellulose lacquers for exterior work have but little application within the sphere of the engineer, but they have proved tremendously popular in the painting of motor-car bodies. The base of cellulose lacquers is cellulose nitrate, obtained by acting upon cotton with nitric acid and sulphuric acid. Cellulose nitrate does not of itself give a glossy or adhesive film, and resins are added to meet these deficiencies, whilst substances known as plasticizers are added in order to give the film the necessary flexibility. Cellulose lacquers dry by evaporation, and the film remains soluble in the lacquer solvents, thus rendering it impossible to build up a thick coat by brushing, although this can be done by spraying.

Although cellulose lacquers have been found to be adaptable to certain industries, they have not been successful for exterior painting so far as railways are concerned; a realization of this, in conjunction with the advantages offered by synthetic resins, led to an investigation being carried out with the object of combining the desirable features of both, since, if this could be achieved, it would produce films of much greater hardness and toughness and, in addition, would fulfil one function which is so vitally important to-day, namely, the speeding-up of painting processes. Considerable laboratory work was carried out, and when a formulation was arrived at which showed promise, a manufacturer was taken into collabora-tion in order to advise on the practical difficulties, if any, of producing such a material in bulk. It was found that the idea was generally adaptable

to modern paint-manufacturing technique; the material was produced experimentally, and, having satisfied all the tests applied to it in the laboratory, was eventually utilized in the painting of locomotives and carriages. It should be noted, however, that this is only rendered possible by utilizing modern methods of paint-application, since it is essential that the material should be applied by spraying. The spraying of such a material does not present any serious difficulties, and it is interesting to note that some fifty coaches were spray-painted by the automatic spraying plant.

Bituminous paints have been improved by processing the bitumen in order to produce a more tough film. In addition, bituminous emulsions are available which have a high resistance to the fault known as "crocodiling" (so called owing to the resemblance between the film showing this fault and the crocodile's skin), the resistance being due to the structure of the film resulting from the evaporation of the water of the emulsion.

Chlorinated rubber gives a paint with excellent resistance to alkalies and acids, and recent improvements have resulted in an increased durability, the lack of which has hitherto limited the use of the material to specially corrosive atmospheres where normal paints would break down even more rapidly. The use of this class of paint offers material advantages to the engineer, and it will find many new applications as it becomes more generally known.

The Painting of Rolling Stock.

The Author feels that no apology is necessary for dealing in some detail with the painting of rolling stock, since the developments which have taken place here are a good example of the translation of laboratory research into painting technique under working conditions.

Preparation—Panel Wash.

With the introduction of steel panelling in the construction of carriages, it became vitally important that the steel should be in a suitable condition for receiving the paint, since, coinciding with this method of building rolling stock, a reduction in the number of coatings was introduced, thus rendering very important the initial treatment of the metal prior to receiving the first coat of paint. After considerable experimental work it was found that, for steel panelling as used in carriage construction, the best results were obtained by washing the surface with a solution which was styled "panel wash." The panels are purchased free of mill-scale and are covered with a non-drying mineral oil at the maker's works. After the removal of the oil at the Company's depots, the panels were found to be liable to corrosion due to handling with hands moist from perspiration, and the panel wash was designed to meet this difficulty. The action of the

wash is fourfold; it removes last traces of the mineral oil, dissolves any rust present, and by its chemical action gives a mild rust-inhibitive effect, and also etches the metal, providing an ideal surface for the adhesion of paint. The formula of the "panel wash" at present accepted as standard is methylated spirit, 80 per cent. by volume, and ortho-phosphoric acid (concentrated), 20 per cent. by volume.

The problem with regard to the sheet used for the construction of locomotive tenders was a somewhat different one, since these sheets are much more heavily coated with mill-scale, which is firmly adherent and cannot be effectively removed by such a treatment. Various methods were employed, such as grinding with carborundum stones and composition rubbing stones in conjunction with paraffin oil, and whilst this removed to some extent the scale, the process was very laborious and costly. Sand-blasting and shot-blasting were, therefore, tried, and it was found that shot-blasting produced an ideal condition for receiving the first coat of paint; it is now employed on a fairly extensive scale. In conjunction with this, flexible disks coated with very coarse carborundum paper were also tried, and these were found equally promising and had the advantage that the plant could be transported to any position in the works, which is not possible when shot-blasting is employed.

New Materials and Application.

Generally in the past, more paint has been applied to rolling stock than was necessary for its decoration and protection, as many as seventeen coatings being often used 10 years ago for a railway carriage to produce a finish somewhat comparable with the old-fashioned style of coach finishing. Early work in the laboratory indicated that this multiplicity of coatings was unnecessary, and the problem was, therefore, to find out how the number of coatings could be reduced without detracting from the appearance and ultimate durability of the paint film. This entailed numerous experiments regarding preparatory treatments, new formulations of paint to produce greater build, and the careful study of drying times in order to reduce the number of working days occupied with the actual painting processes to an absolute minimum. Eventually it was found by a readjustment of formulation that the necessary build could be produced and drying times regulated so as to fit in with production problems without causing any derangements. The practice eventually standardized involved the application of eleven coats as against the seventeen previously applied and the time required for actual painting was reduced by 30 per cent.

Carriage Cleaning and Wax Treatment.

While these experiments were in progress, consideration was also given to after-care and maintenance of the painted surface in an effort still further to extend the known durability of paint films on railway rolling stock running under normal conditions. The idea was conceived that the

periodic application of a mixture which would both clean and feed the paint film would have the desired effect. Over two hundred and fifty mixtures were examined, and finally a composition was obtained which justified a practical trial under working conditions. The mixture was applied at intervals of 4 to 6 weeks, depending on the dirty condition of the paintwork, and the coaches were dry-wiped on the day after the application of the mixture. Water-washing was then adopted as an intermediate clean until a further application of the composition was necessary. This composition, which is known as waxing composition, was applied to practically the whole of the locomotive and carriage rolling stock of the L.M.S. Railway, but owing to certain difficulties regarding facilities for application, the treatment has now been reduced to four per annum; there is little doubt, however, that it has achieved its object in that the life of the paintwork has been extended by more than 50 per cent. over that previously hoped for. Two types of waxing composition are in general use, one being applied to rolling stock immediately after it is varnished in the works as a preparatory treatment before the vehicles go into service. The composition used in this case is as follows :—

Ceresin wax	16 per cent.
Calcium stearate	10 ,,
Petroleum	30 ,,
Mineral cleaning oil	44 ,,

This composition is intended as the initial protection to the varnish, but its cleaning properties are such that it will not function satisfactorily when the paintwork becomes coated with traffic grime. It is, therefore, necessary to incorporate a mild abrasive for this purpose. A typical formula of the wax cleaning composition is as follows :—

Abrasive powder	33 per cent.
Calcium stearate	3 ,,
Ceresin wax	7 ,,
Oxide of iron	2 ,,
Carbolic acid	0·5 ,,
Petroleum	53 ,,
Ammonia (concentrated)	1·5 ,,

Reduction in Coats and Time.

Appreciating that there is a loss of revenue for each extra working day that carriages are out of service for painting, experiments have been started and are well on the way to completion which should lead to a further reduction in the number of coatings applied through the introduction of the nitrocellulose–synthetic-resin process mentioned previously, and also through modifications of synthetic resin enamels. These materials will stand up to service conditions as well as, if not better than, the methods usually employed and will considerably speed up the drying times, with a consequent reduction in the number of coatings and in the actual time required for the painting operations. Advantage was taken of the progress

made in the development of synthetic-resin finishes to treat the "Coronation Scot" train throughout with this newest type of finish, and an examination of this train will provide striking evidence of the superiority of this treatment over the orthodox type of varnish finish previously accepted as standard.

Interiors—Reviver and Stripper.

The interior decoration of carriages has also been carefully studied, since old-fashioned types of finishes embodying varnish and french polish left much to be desired so far as appearance was concerned, and were also very costly in their upkeep, as they required fairly frequent renovation and partial re-coating in order to bring out their decorative and protective properties.

Early experiments were started with various types of cellulose finishes, embodying nitrocellulose and butyl cellulose. These were standardized and covered by suitable specifications in order to govern their essential properties, and the basis of the present L.M.S. Railway cellulose specifications is fairly universally applied throughout the cellulose-lacquer manufacturing industry. Newer developments have called for the introduction of quick-drying synthetic resin finishes and combinations of varying types of cellulose in conjunction with synthetic resins. These show promise of producing more durable films, and incidentally lend themselves much more readily to renovation than the older types. The question of renovation is an all-important one, and appreciating this, the Author commenced a series of experiments with the object of producing a reviver which could be universal in its application, irrespective of the type of finish it was to be used upon. Considerable difficulty was experienced in making such a reviver generally adaptable, but eventually an entirely satisfactory product was produced and subsequently patented. In conjunction with this, where cellulose or other films have been damaged through abrasion and misuse, it is often necessary partially to strip such coatings in order to restrain and fill the wood and bring it into a condition suitable for recoating. Here again various types of stripping materials were available for each type of painting material, but at that time a stripper which could be universal in character was not available. Experiments were started with the object of producing such a material, and after many works' trials with different laboratory formulations, a material possessing all the essential features necessary for stripping paint, enamel, varnish, french polish, and cellulose coatings was evolved. A typical example of the stripper, which has been patented, comprises the following:—

Ceresin wax	7 per cent.
Benzol	21 ,,
Methyl alcohol	20 ,,
Ethylene dichloride	32 ,,
Acetone	20 ,,

It must be appreciated that variations in this formula can be made according to the type of surface to be dealt with.

Painting of Structures.

The Author realizes that the painting of structures in the open presents greater difficulties in control than is the case with painting operations carried out in shops. Nevertheless, he feels that a great deal of control can and should be exercised in insisting that the surfaces are in a satisfactory condition for receiving paint, and in paying due regard to the conduct of painting operations in relation to such external conditions as weather. One of the most important factors influencing durability is the preparation of surfaces prior to painting, particularly in the case of steel.

Preparation of Steel for Painting.

Weathering is the method most commonly adopted in de-scaling. Careful investigation has shown, however, that under modern conditions the de-scaling by weathering is often incomplete, and that at least 6 months' weathering is required to remove all mill-scale. It is true that in former times weathering was an effective method, because it was possible to allow it to proceed until all mill-scale could easily be removed. Whilst the question of the desirability of complete de-scaling is still a controversial one among engineers, gradually, amongst the scientific investigators into corrosion, unanimity is being reached. A most important factor is that the condition of pitting is favoured when the corrosion is localized by the presence of a broken film of scale. When the metal is to be painted, another characteristic of scale assumes importance—its low power of adhesion. No matter how carefully a scale-bearing plate is painted, if the whipping of the plate under service conditions results in the detachment of the scale from the base metal, the paint film becomes detached with it, and the conditions for corrosion are set up, resulting eventually in the breaking of the paint film and in the appearance of bare patches of steel.

From these considerations it will be seen that in spite of the initial expense the practice of removing scale completely (partial removal, as has been seen, results in worse corrosion than the presence of a complete film of scale) is essential if corrosion is to be avoided. So far as the L.M.S. Railway is concerned, the de-scaling and preparation of metal for painting is carried out with the utmost care, and often the cost of preparing the metal far exceeds the cost of painting it.

Returning to the consideration of the methods of descaling, weathering, although satisfactory under certain circumstances, is too often liable under modern conditions to result in incomplete removal. On account of its simplicity, however, it may be supposed that the method will long continue to be used, and the following procedure will be found to give the best results :—When the time has come for the application of paint, the

whole surface should be thoroughly wire-brushed, and as much as possible of the scale removed by hammering (the efficiency of which method goes to prove the necessity for it). A coat of priming paint containing one of the inhibitive pigments should be applied immediately after the cleaning and de-scaling operations.

De-scaling by pickling is the method which has most to recommend it, and recent improvements introduced have revolutionized the whole problem. One method in particular, which has been adopted by a large industrial concern, has proved very successful, and is considered of sufficient interest to justify the details of the method being given here. The steel is first de-scaled in a 5-per-cent. sulphuric-acid bath maintained at a temperature of from 60° to 65° C. When the plates are completely de-scaled, they are washed in hot water, and finally immersed for from 3 to 5 minutes in a 2-per-cent. phosphoric-acid bath at a temperature of 85° C. They are then primed while still warm from the bath. The cost has been calculated to be less than $\frac{3}{4}$*d.* per square foot, and the results obtained are excellent.

Plates treated by this method (and afterwards painted) 4 years ago are still in an excellent condition, whereas it was necessary before the introduction of this method to repaint after 1 year. Other methods of pickling employ hydrochloric acid, sulphuric acid, or phosphoric acid used alone, sometimes followed by washing in a neutralizing bath of lime; the plates so treated are generally liable to re-rust very quickly, a tendency which is checked by the use of the method given above.

Sand-blasting, shot-blasting, and grinding are the mechanical methods most favoured, with such variations as shot- and sand-slinging, tumbling, etc. Sand-blasting and shot-blasting are similar processes except (as the name implies) as regards the nature of the abrasive, and both are very efficient. Grinding is rather expensive, and has the additional disadvantage that there is some danger of the metal being flowed over the scale and imprisoning it, thus setting up the conditions for corrosion.

A method which has a limited application but which is much favoured in certain trades is that of stretching. The scale-bearing metal is stretched about 10 per cent. of its length, the scale being almost completely detached by the process. It is important to follow up immediately the stretching operations by wire-brushing, and by the application of the priming coat of paint. The stresses induced do not appear to have any serious effect upon the subsequent life of the metal. Bars and plates 10 feet by 4 feet can be treated in the manner indicated.

The Influence of Atmospheric Conditions at the Time of Painting.

The second factor which may have a predominating influence on the life of a protective paint system is the condition of the weather at the time of the actual application. It must not be supposed, of course, that the Author has overlooked the effect of the atmospheric conditions during the life of a paint, or that the influence does not differ from place to place or

even from time to time, but this is a factor which is outside the control of the engineer, although he can vary the paint to meet any circumstances, there being wide differences in the ability of paints to withstand particular conditions. The engineer has the power to interrupt painting during inclement weather, and the wise one will insist that painting is not allowed to proceed when the surface is moist, either as the result of rain, or because the temperature of the structure is below the dew-point; in the latter case this can usually be avoided by delaying the application of paint until after, say, 9 o'clock in the morning, the first period being occupied by preparatory work. To apply paint when the weather is frosty is to court disaster. Wherever possible, a close season for painting should be observed between the 1st November and the 1st March so far as exterior work is concerned, but generally speaking these months can be occupied in the painting of interiors. Where circumstances make it impossible to wait for ideal conditions, spray painting should not be employed, but vigorous brushing should be enforced, since by such action the water tends to become emulsified in the paint and can evaporate from it. Sprayed paint, or paint brushed out with a minimum of effort, results in the water present on the surface being imprisoned below the paint film, and, in consequence, corrosion results, and the paint forms blisters and becomes porous. Paints differ in their behaviour when applied under adverse conditions, and although some are less affected than others, none give the best results unless applied under the correct climatic conditions.

Methods of Application.

Spray-painting, although engineers do not yet accept it with complete confidence, is firmly established in certain industries; indeed it would be difficult to find a large motor-car production shop which does not rely entirely upon spray-application, and it is certain that, in the majority of cases where spray-painting is said to have failed, the real reason for the failure is the use of incorrectly manufactured paint, improper preparation of the surface, or unfavourable weather conditions. The practice, common among spray-painting equipment manufacturers, of telling prospective customers that any paint can be successfully applied by spraying is dangerous and quite incorrect, and has done much to bring about the present cautious attitude to spray-painting now common among engineers. Great improvements are continually being made in spraying equipment, and operation-difficulties are gradually being overcome. The principle of spraying is the atomization of a stream of paint supplied to the gun nozzle by pressure from a separate vessel which contains the paint under 1 or 2 atmospheres pressure, by gravity from a container attached to the top of the gun, or by suction to the nozzle from an underslung container by the passage of compressed air over the top of a supply tube immersed in the paint. The atomization is accomplished

by compressed air at a pressure which varies for different systems from 8 lb. per square inch to 60 to 80 lb. per square inch.

The gun is so called because of its trigger control. Upon applying a slight pressure on the trigger compressed air is released, which may be used for dusting or blowing away any foreign matter lying upon the surface to be painted. Further pressure operates a needle valve releasing the flow of material, which is then atomized by the compressed air. Correctly placed orifices in the nozzle through which compressed air passes serve to give a fan shape to the stream of atomized paint. This has the effect of widening the area coated with each stroke of the gun. The atomized paint, coming into contact with the surface against which it is directed, is flattened out and coalesces into a continuous film. The action of the spray-gun in releasing the air before the material is looked upon by some authorities as vitally important. They complain that paint failures have been traced to the fact that dust has been worked into the paint film during the brushing operation, and feel that the facility with which efficient dusting can be done with the aid of the compressed air ought to have an important bearing upon the durability of paint applied by spraying.

The type of apparatus best suited to the painting of structures such as bridges and buildings consists of a petrol-driven compressor, capable of delivering 3 to 4 cubic feet of air per minute per gun at a pressure of between 30 and 60 lb. per square inch. A gun nozzle of 3 millimetres diameter is satisfactory. The paint should be supplied from a pressure container at a pressure varying from 10 lb. to 30 lb., according to the height (a pressure of 30 lb. is sufficient to supply paint to a gun working at say 20 feet above the container). If the required height is much in excess of this, it will be found to be the best practice to elevate the container. The actual area covered for solid surfaces is from four to six times as great as can be brush-painted in the same time, which enables full advantage to be taken of favourable weather conditions.

In bridge-painting, where so often important parts are inaccessible to the brush or are laborious to coat properly, spraying will be found to bring many of these areas within easy reach. It is essential to strain all paint before placing it in the pressure-container; the omission of this simple precaution has been responsible for many hours of delay. Another important precaution is that of drying and cleaning the air used. All spray-painting compressor units should incorporate an air purifier and drier. As air is compressed a certain amount of moisture is condensed and this, if it finds its way into the paint film, will do much damage, whilst the presence of oil from the compressor in the air used for atomizing the paint is liable seriously to affect its properties.

So far as the physiological effect upon the operatives is concerned certain precautions should be observed. The spraying of lead paints should at all times be avoided. The use of masks, except where a strong wind is blowing the spray dust away from the operator, should be insisted upon

Unfortunately, masks are uncomfortable to wear, and operatives object to their use. The best type of mask is of rubber, designed to cover the nose and mouth, and fits closely to the face. The filter consists of a number of cotton-wool disks through which the air is drawn. Attached to the bottom of the filter projection is a valve of generous proportions, which consists of two flat pieces of rubber in contact. When the breath is drawn in, air-pressure closes the valve, resulting in all the air reaching the wearer passing through the filter. On breathing out the slightest increase in pressure opens the valve, and the foul breath is easily dissipated. It must be remembered that the mask which has been described is only effective in removing dust and solid particles, so that all toxic volatile constituents must be avoided in spray paints. Constant attempts are made with greater or less success, and new guns designed, to minimize "spraying fog," which is the result of paint particles rebounding from the surface against which they are directed.

On the L.M.S. Railway serious attention is being given to spray-painting in all its aspects, and at present it is being used in the painting of wagons, road vehicles, stations, etc., and in the application of cellulose finishes in the interiors of carriages.

The training of the operative can have a very important bearing on the results obtained from spray-painting. The untutored spray-painter almost invariably uses the gun as he would the brush, passing over the same area several times and flexing the wrist so that the angle of the gun to the surface is continually changing. It is important that the gun should be held at right angles to the surface, so that a uniform film is obtained. The Author has organized a school for spray-painters, and the results have fully justified such a course, one important result being that the maintenance costs for guns have been reduced. The mechanism of spray guns is intricate and can with careless use be quickly thrown out of gear, but if the operative has been trained in its care a spray-gun should give many years of uninterrupted service.

The Influence of the Type of Surface.

The influence of the type of surface of the metal employed has, generally speaking, only a small influence on the life of the paint applied over it. Wrought or cast iron does not corrode so quickly as ordinary mild steel, and paints applied over them normally have a slightly greater life. Copper-bearing steel has been shown by the Corrosion Committee of the Iron and Steel Institute to be superior to a steel without such addition, but the general conclusion of the Committee was that none of the steels available for industrial structural work have sufficient resistance to corrosion to make its protection by painting or other protective coats unnecessary.

Conclusion.

Appreciating that so many factors are outside the direct control of the engineer owing to the wide area throughout which he has to operate, it is the Author's belief that the most essential factor to safeguard the engineer's interest is that paint should be purchased in a ready-mixed form and used exactly as received. All the essential properties of the paint can be taken care of in specifications, and such a procedure, calling for co-operation with the manufacturer, ensures that a high standard of quality is maintained.

It must not, however, be assumed that the provision of high-class painting will cover up errors which may be due to lack of control, to the neglect of points which have previously been mentioned affecting the preparation of surfaces, and to application under incorrect conditions. In a study of the weathering properties of paint during the last 16 years, the Author has found that many of the best paints have failed through lack of consideration of these factors. These difficulties, however, are fully realized, and it must be said that much is being done to counteract them. Although some progress has been made in producing paints which are less susceptible to conditions of application, the Author feels that it will be a long time before development has reached a stage at which it will be possible to relax the present precautions in the preparation of steel surfaces prior to painting.

The Author acknowledges his indebtedness to Sir Harold Hartley and Mr. T. M. Herbert for making available much of the information quoted, and expresses his deep appreciation of the great help afforded by Mr. F. G. Dunkley in the preparation of details and in reading proofs.

Discussion.

The Author exhibited a number of lantern-slides in illustration of his Paper. He observed that the Paper was intended to set out as clearly and concisely as possible what could be achieved by studying paints in the light of scientific developments and scientific control. It had been kept within reasonable limits of size only by the strict avoidance of detailed descriptions in general and descriptions of individual apparatus and operations in particular. His remarks would therefore be directed to filling in some of the gaps, in order to enable a proper appreciation of the work of the paint laboratory to be obtained.

Four exposure-racks were utilized by the Laboratory to test the weathering properties of paints, as paints were not judged on specifications alone but on performance. One rack was on the roof of the paint laboratory, and another was at ground level; the third was in a marine atmosphere, and the fourth in a railway tunnel. All the panels were exposed at an angle of 45 degrees, as his experience had shown that that gave the most comparable results, and varied exposures were given. The coats were applied in the same manner, number and sequence as they would be under service conditions. An industrial atmosphere caused more rapid breakdown of films than a marine atmosphere. It was necessary to keep the most complete records possible of the effect of the exposure given, and all the relevant details were recorded on an exposure-record chart. The same chart was also employed for accelerated exposures. By careful analysis of the records, it had been possible to classify paints into very well-defined categories. In cases where the process or the paint was of particular interest, the panel was photographed on the termination of the exposure, and such photographic records were particularly helpful in assessing the rust-inhibiting properties of various paints and pigments.

The opacity of paints was studied by brushing out a measured volume of paint over a specified area of a black-and-white chequered board, and the result compared with that of a standard paint. That method was to some extent dependent on the human element, as it was difficult to get two operators to brush out paint in a similar manner; in order to overcome that difficulty another method was being tried at the present time, but was not yet sufficiently advanced for a description of it to be given. The building-up of such tests was of vital importance in obtaining a true comparison of those properties that could be determined only by the operator himself.

The chemical testing of paints usually involved apparatus and methods similar to those in general use in chemical laboratories. There was, how-

ever, one chemical test to which it might be of interest to refer, which was used in checking the resistance of synthetic resin materials to attack by acids and alkalis. The specimen was coated over with paraffin wax, which was removed in two places to expose the material. One place was spotted with an alkali and the other with an acid of known strength, and the effect observed. Evidence of slight action by either showed the material to be unsatisfactory. That test was one of a series that was gradually being introduced to take the place of the ordinary chemical tests which had been applied in the past. He believed that the chemical control of paint supplies, while serving a useful purpose in certain respects, had rather outlived its purpose; it was necessary to develop physical tests that would have a direct bearing on the actual performance of paints and would thus indicate the conditions which paints had to fulfil. It would then become possible to specify the performance required from a paint and to leave it to the manufacturer to make use of his own research facilities and to employ whatever materials he found to be the best.

A simple apparatus had been devised to test the fire-resistance of paint. A standard small gas-burner was so regulated that the length of the flame was 1 centimetre, and the flame was allowed to impinge on the surface to be tested for 15 seconds, the degree of inflammability being judged from the area that had become charred. Any material that had a char longer than 1 centimetre was considered to be unsatisfactory. That test had been of particular value in dealing with the newer types of wood finishes.

It was necessary in certain specifications to indicate the degree of flexibility which was desired in the finish. For that purpose small strips of metal were coated and allowed to dry for fixed periods, according to the type of the material, and were then bent double over a $\frac{1}{4}$-inch rod. Some of them were bent at ordinary temperature, and others at freezing point. In carrying out those tests by hand, it was very difficult to ensure the same time of bending in each case, and the speed of the bend influenced the result considerably. So much importance was attached to that test, particularly for varnishes, that a constant-speed mandrel apparatus had been developed in which the specimens were bent at a constant speed. The time of bending had been fixed at 1 second.

Experiments on paint and varnish films with a small tensile-strength machine had proved useful. The effect of various types of varnishes on various types of under-coatings was being studied with that machine in order to see how extensibility and breaking load affected breakdown in paintwork. The point was of particular interest in connexion with the newer types of synthetic resin varnishes, where, owing to the rapid speed of hardening, unless the undercoats were satisfactory the varnish simply pulled them away and a very aggravating "crocodile" appearance resulted.

In translating laboratory experience to shop conditions, it was not considered sufficient to specify a process and the materials embodied in

t. The laboratory, collaborating with the Chief Mechanical Engineer's department, watched the application and the results of the process, so that they could speak with authority on every aspect of it and could advise the works on those points of application which were so vitally important. It was necessary to obtain the maximum possible life from the paints, and therefore the quality of the materials, the preparation of the surface to receive the paint, and the application of the paint all had to be rigidly controlled. Where there was any danger of a job having been skimped, small sections of the film were removed and their thickness checked by spherometer.

The artificial weathering plant employed (p. 147) was of the standard type, as developed in America. In conjunction with other pieces of physical testing apparatus, its use was part of the everyday policy employed in the defining of the essential properties of paints and painting materials. The experience gained with the apparatus in question during the last 7 years had been so valuable that an entirely new apparatus, embodying the same principle but with certain additions, was now under consideration.

In the Paper particular attention had been directed to the preparation of steel prior to painting, as the average engineer was apt to pay insufficient attention to it. No paint could overcome deficiencies in the preparatory work undertaken before it was applied. Methods for the preparation of steel had therefore been investigated on behalf of the L.M.S. Railway, and he himself had been doing some work on the subject in conjunction with the study of protective coatings by the Corrosion Committee of the Iron and Steel Institute. Both shot-blasting and sand-blasting had been tried, and a method of shot-blasting had now been standardized for dealing with plates prior to painting. An alternative method that had been applied was the use of a high-speed pneumatic rotary flexible-disk machine, employing a detachable carborundum-cloth disk. The results obtained were excellent, but not so good as those of shot-blasting; there was the disadvantage that often after such grinding, which was best done prior to erection, the plates had to be handled to a considerable extent, and delay often occurred before painting was carried out, which led to rapid corrosion. Mild steel as used for panelling had a very high-class charcoal finish, and in its highly-polished condition was quite unsuited for receiving paint. In preparing it for painting, as described on pp. 153 and 154, an acid wash was applied and was allowed to remain on for a fixed period. The plate was afterwards washed with hot water, and immediately it was dry it received its first coat of paint. It should be emphasized that it was no use carrying out that process and then putting the panels aside and painting them the next day; it had been proved by experience that to obtain the full benefit from the process the painting had to be carried out with the least possible delay. Particular attention was paid to the preparatory treatment described, as it could make or mar the painting.

To illustrate the advance made in painting L.M.S. railway stock, it

might be stated that in 1930 seventeen coats had been used, taking 21 days, whereas the current schedule provided for ten coats in 15 days, whilst a schedule under consideration provided for six coats in 9 days. It might be argued that it was not possible to reduce the coatings and the period of painting in such a way without sacrificing durability, but within limits the reverse could be the case; by careful attention to several important factors greater durability had been achieved with the current schedule. Firstly, the paints were formulated and the quality of the raw materials watched very carefully, and a system of control was exercised in the works so that formulas were rigidly adhered to. Secondly, a great deal of attention was paid to the preparation of surfaces. Improvements in the methods of after-care and maintenance were the last of the major factors responsible for that increase in the life of the paintwork of rolling stock which was now an established fact.

With regard to after-care and maintenance, it would be appreciated that a railway coach was cleaned some hundreds of times during its life, and the cleaning agents and the methods of cleaning had a very important effect on the life of the paintwork. The use of waxing compositions for cleaning had the effect of "feeding" the varnish; they caused to be retained in some small way the flexibility which the varnish normally lost during the ageing process, and retarded crazing and cracking.

Spray-painting had been developed to a high degree of efficiency. In the early types of spraying apparatus, the cup was fitted to the gun and carried only a very limited amount of paint, making frequent additions to the paint-supply necessary. In later forms of spraying plant the paint-reservoir was separate and would carry sufficient paint for a working period. It was desirable to emphasize that a man who was to do spray-painting had to be thoroughly trained. The spray-painting gun was an intricate piece of mechanism, and to bring out its full possibilities the man who used it had to have some knowledge of what he was doing, and should be skilled in the regulation of the pressure according to the type and consistency of the paint which was being applied. Sight was frequently lost of those factors, and users imagined that a paint could be applied in the same way from whatever source it came. That, however, was totally incorrect. When the use of spraying was contemplated for the road motor department of the L.M.S. Railway, all the men to be engaged in spray-painting were taken into a school and taught the elementary features of the gun; the mechanism of the gun was deliberately unset and they were made to re-set it, and the process was fully explained. The value of the experience which they gained in that way had been translated into the improved work which they subsequently did. Spray-painting badly applied could spoil very good paint and rob it of its essential properties, but when properly applied it was in his opinion the method of the future. Experiments had been made with an entirely automatic spraying machine for painting coaches, in which a spray-gun was traversed

ertically over the surface to be painted. The machine ran on rails and vas propelled about 5 inches with each upward and downward sweep of he gun. At the top of the machine was an exhaust-apparatus containing affles and filters so that all the paint particles were removed before the xcess air passed to the atmosphere. Spray-painting had been applied o about two hundred locomotives, and the saving in time as compared vith brush painting was about 30 per cent., quite sufficient to justify the xtension of the procedure.

In conclusion, he would emphasize that the performance of paints was ot judged on laboratory experience alone. The laboratory experience, he experience so far as ordinary exposures were concerned, and the in-ormation available from service tests were all taken into consideration, o that the final expression of opinion on the essential properties of any aint was as broadly based as possible.

Mr. M. F.-G. Wilson, Vice-President, congratulated the Author on most interesting Paper. He himself had had very little experience of ainting, but he had been connected with the Sea-Action Committee f The Institution since its inception, and Dr. J. Newton Friend had arried out a series of paint-experiments [1] for that Committee which were xceedingly interesting, though they were not nearly so elaborate as those lescribed in the Paper, because in the circumstances such elaboration was hot necessary. The object of those experiments had simply been to ind some coating that would preserve steel and iron from the effects of weather, without any regard for finish. There were, however, several aspects of the two sets of experiments that might usefully be compared. The Author had found that spraying was the best method of applying paint for railway equipment, but the experiments conducted by the Sea-Action Committee had shown that it was to be preferred, for their purpose, to apply the paint fairly heavily with a brush and to brush it well in. Because of the different conditions as compared with those dealt with in the Paper, they did not use nearly so many coats of paint as did the Author; at the most they used three coats of paint, whilst with some of the bituminous paints tested they applied one coat only. For purposes of comparison a standard paint was adopted, consisting of two coats of iron oxide with linseed oil as the vehicle. Other paints tested and compared with that standard included white lead, red lead, red and white lead mixed, various other pigments, and tar and bituminous paints; galvanizing was also tested.

The Committee did not employ any mechanical tests to the paint-film such as those described by the Author; they merely applied the paints to the plates and then left it to nature to test them, the painted plates being exposed to the effects of sea-water and sea-air at Southampton and

[1] "Deterioration of Structures of Timber, Metal, and Concrete Exposed to the Action of Sea-Water" (Fifteenth Report of the Committee of the Inst. C.E.), pp. 81 *et seq.* London, 1935.

at Weston-super-Mare. Sets of plates were exposed above high-water, others at half-tide, and others below low-water; they were left for periods ranging from 1 to 7 years, and were then removed for examination. The value of the preservative method used was taken as being measured by the loss of weight experienced by the plate during the period of exposure, the plate which lost the least weight being considered the best.

Generally speaking, it was found that the lead paints, red and white, were a little better than the iron-oxide paints. Fairly heavy galvanizing, to the extent of 20 ounces per square yard, proved very successful. Bituminous coatings were found to be especially good in the half-tide and submerged positions, but not so good in the aerial position. The best and most reliable results were obtained with tar compositions, which provided excellent protection. It was also found that if three coats of shellac varnish were applied over tar, coloured paint could then be applied if desired, and gave very satisfactory results.

Dr. L. A. Jordan observed that in the Paper and in his introductory remarks the Author had well set out the leading features of modern methods of paint-testing. The Paper, however, was much more important than that, and he would recommend those interested to read a Paper by Sir Harold Hartley entitled "Scientific Research on the London, Midland and Scottish Railway."[1] The present Paper keyed in admirably with the more general scheme described therein. Sir Harold referred to the relationship between the railway research-organization and the national research-organizations, of one of which, the Paint Research Station, Dr. Jordan had the honour of being the director. Unfortunately the Railway was not a member of his research-organization, as the constitution of the Paint Research Station did not admit the users of paint as members. He thought that that was a very great pity, because there was no doubt that the interesting and useful part of the life of paint began only after it had left the paint-manufacturer; the Author's remarks led up to what was a very favourite theme of Dr. Jordan, namely, that it did not matter so much what was in the tin as what was done with it. He would commend that thought to those who were faced with disappointments in the use of paint; there was more than a substratum of truth in it, and a particularly valuable part of the present Paper was the Author's description of how a close examination of the conditions of application and of the surface to which the paint was applied could influence the performance of paint films, and ultimately the formulation of the paints. The section of the Paper which dealt with the painting of structures, the preparation of the iron and steel, and the influence of atmospheric conditions was one which should be studied by all who were interested in or concerned with similar painting problems; it would also be of value to paint-manufacturers.

In his own work on the problems in question it was necessary to take a

[1] Journal Inst. Transport, vol. 13 (1931–32), p. 495.

oint of view rather different from that of the Author. The Paint Research tation had to maintain a wider and more general approach, and to deal vith the various problems on an even more fundamental basis. Those roblems were essentially "long-distance" in character, and it was fitting hat such problems should have a special claim on the attention of the taff of a co-operative research-organization.

On pp. 143 to 148 reference was made to the preparation and use of specications, which at the present time tended towards definition of composition. 'he paint trade did not like specifications, but he could well understand vhy the Author did. The Author had pointed out, however, that the ltimate criterion was that of performance-tests. Those tests were essenially physical, but they were very difficult to interpret; even when an nterpretation was made, it was very difficult to persuade people to accept t if it did not happen to suit them to do so, and therein lay the weakness of he present situation. What was really wanted, in Dr. Jordan's view— nd he did not regard it as altogether impossible, though it might be difficult —was a series of tests on the paint film which would take no more time nd involve no more distress to the paint film than a medical man gave to a erson whose prospects of life he was examining for the purpose of an inurance-policy. If a medical man were to treat his patient as a paint lm was treated at the present time, the patient would be in a very sorry nd battered condition before any decision was reached as to his prospects f survival! The analogy might not be perfect, but it would give an idea f what he had in mind; it was a pity to have to spend so much time testing naterials to destruction in order to estimate their prospects of survival. t would be very useful to be able to estimate the weather-resistance of aint much quicker than was now possible, but the difficulty with ccelerated tests was that the more they were accelerated, the more they ecame dissociated from reality; it thus became necessary to effect a ompromise.

He could illustrate the point in another way by pointing out that the elationship between pigment and medium in a liquid paint was determined y the conditions at the interface. When a liquid paint was spread a lm was formed, and the structure of that film was again dominated by he interfacial layers and modified by conditions of application. Finally, vhen the paint film in its old age was beginning to show signs of wear, the nanner and extent of breakdown of the structure was again determined y the interfacial layers. It was thus evident that the extent to which he performance of paint was determined by the simple chemical composiion of the main components was in many cases slight in comparison with he effects of other factors such as those that he had mentioned.

† **Mr. Ernest Pugson** observed that many valuable contributions

† This contribution was read on Mr. Pugson's behalf.—Sec. Inst. '.E.

to modern railway theory and practice had been made by the late Mr. R. W. Reid, but it was doubtful if any would have a more permanent or far-reaching effect than the recommendations which he made as Chairman of the Committee set up by Sir Josiah Stamp in 1928 to consider the need for more extensive scientific research on the L.M.S. Railway. The resulting establishment of the Research Department could not have been made at a more opportune moment, for it coincided with a period of great activity in the modernizing of methods within the L.M.S. Railway. The changes brought about had created new problems, some of which were submitted to the Research Department. Among those problems were a number concerning painting, the satisfactory solution of which the Author had been able to record in his Paper. It was a feature of the organization that close co-operation between the Research Department and the Department in which the problem originated was maintained, and the facilities which were afforded to the originating Department for watching each step of the investigation served to create that co-operation which was essential to success.

With regard to the control of supplies, the standardization of painting practices implied the use of standard materials of standard quality, whilst the smooth running of the piecework system required the uniformity of such properties as ease of application. The work of the paint laboratory, so far as it concerned the control of supplies, was an essential feature of works organization, and the strict control maintained had eliminated much trouble in the works.

The interior decoration of cars had always presented difficulty owing to the destructive action of sunlight passing through the large windows of corridor stock; it brought about the failure of french polish in a period of 4 or 5 years, and in extreme cases even earlier, by the formation of large numbers of small blisters. Early experiments in the use of cellulose lacquers had often been attended by even worse blistering than had been experienced with french polish, but that had been found to be due to the addition of polish to the lacquer and to incorrect formulation. The problem had been submitted to the Author, who drew up specifications for the lacquer; lacquer as specified had proved to possess a life of 11 years, thus justifying the course adopted.

Regarding the use of panel wash, it had been appreciated, when the wood panelling of cars had been abandoned in favour of steel sheeting, that maintenance-costs would depend upon the degree of efficiency of the measures taken to combat corrosion; much thought had therefore been given to that problem. The adoption of the phosphoric-acid panel-wash recommended by the Author had resulted in complete freedom from corrosion occurring under the paint, and flaking of the paint had been entirely eliminated. There remained one problem, however, which required attention, namely, the prevention of corrosion at the edges of the panels round the windows, always a weak point. The method of treating the

panels with phosphoric acid was more efficient for the type of sheet used than sand-blasting, was cheaper, and could be carried out anywhere without any precaution other than the provision of rubber gloves for the operators.

With reference to new materials and their application, the Author had mentioned the reduction of the number of coats in the painting of the exteriors of cars, which had been effected in 1933, in spite of the pessimistic prophecies of painters of the old school. After 5 years' operation, however, he could state that the protective value of the new painting system was satisfactory and that the standard of finish had not materially suffered.

The reference on p. 152 to the Author's investigations that led to the development of a new type of finish was interesting. That material had been used in the form of a clear lacquer on the interior woodwork of many cars. As was inevitable, some difficulties had been experienced in the early stages, but, following a modification of the materials, it was found possible to employ the normal methods, and excellent results had been obtained. The new materials possessed greater "body" or film-forming properties, and, provided that the durability under service conditions proved as satisfactory as was indicated, a considerable advance would have been made over materials formerly available. So far as the use of the new materials for exterior work was concerned, the larger question of extending the spray-painting of cars was involved. In the meantime, the cars which had been painted with the new material were now under observation. One remarkable property had been revealed, namely, that the gloss improved during service and under the influence of the cleaning operations. The orthodox varnish finish, on the other hand, was very adversely affected by them. Methods of application constituted a complex question, for which the criteria varied from factory to factory, and even from shop to shop. If expensive exhausting equipment and air-conditioning plant were to be provided, the capital cost, as well as the cost of moving vehicles to a fixed point for painting, would have to be considered in each case. A further point to be considered was that of material-consumption, as it might be so high as to negative the saving in labour-charges effected by spray-painting. There was no reason to believe, under shop conditions, that brushwork was superior to spraying.

Mr. Pugson had had an opportunity of observing closely the cleaning of carriages with a wax preparation, and there was little doubt that it fed and preserved the paint. It was of particular value on wooden carriages where mouldings were involved, as any cracks in the mouldings were filled in by the wax, thus preventing water from entering. He found, however, that the operation needed very close supervision and that a good deal of hard work was necessary; in order to prevent discoloration the waxed surface had to be wiped clean.

He had carried out many experiments with the reviver and the stripper mentioned on p. 156; used in the open air or an open shop the stripper

was very satisfactory, stripping quickly and cleanly, but when used in confined spaces such as railway-cars, the fumes given off by the constituents caused difficulty, and before the stripper could be used on a wholesale scale, efficient ventilation would have to be devised. The reviver had proved a valuable addition to the available material for keeping the polished work of the interior of cars in an attractive condition.

Mr. H. G. Lloyd, speaking from the point of view of a resident engineer, remarked that it was not far from the truth to say that the bugbear of most engineering jobs was the paint, as it was often difficult to apply it even to a properly-prepared surface, and difficult to ensure its durability. About 35 years ago, when he had had trouble with a paint it had been possible, thanks to the assistance of chemists, to find out what was the matter; although the manufacturer would not believe them at first, he was very grateful in the end, as he had been enabled to put the matter right. The present Paper showed how much progress had now been made in paint-research.

About 9 years ago, he had tried to make up a paint which could be applied to cement or concrete. Such paints had not been referred to in the Paper, although presumably a railway company would often require them. He had employed a mixture of latex and aluminous cement, though English aluminous cement had been in its early stages at that time. He would not claim that it had been a success, but it had since been developed by a friend of his, and a rubber-and-cement coating was now on the market and could be used on flexible material and bent with very satisfactory results. In order to test its strength, he had carried out some tests in which samples had been coated with the material, forced together, allowed to dry, and tested in tension. The tensile strength was 100 lb. per square inch, which was quite good. It would be interesting to know how the Author carried out tensile tests on his paint films; were they on a surface of metal or other material which was stretched at the same time? It would be difficult to carry out a tensile test on the film itself.

In order to test a paint for wear, he had tried dripping water on it for a considerable time, as that seemed to be a very severe test, especially with a drop of about 10 feet. The rubber paint to which he had referred had successfully withstood that test, as well as bending tests, which seemed to show that the material might be suitable in some cases where ordinary paints were not.

There was a remark on p. 144 that should be borne in mind, namely "It . . . is not sufficient to prepare specifications and schedules and to leave them to the works control without ensuring that the accepted standards are actually being applied in practice."

Mr. R. L. McIlmoyle remarked that, as he belonged to the Chief Engineer's Department of the L.M.S. Railway, his comments would be designed to show how the Author's work had helped them, and to deal with some of its applications.

The Author said on pp. 158 and 159 that it was desirable that painting outside should be confined to certain periods of the year. From a theoretical point of view Mr. McIlmoyle was in entire agreement with that suggestion, but it was almost impossible to apply it in practice. It was not always feasible to find indoor painting which could be carried out during the winter, and, particularly with a maintenance-organization, it was not possible to lay off the painters. It was therefore necessary to carry out certain outdoor painting in that period and to try to find some means of overcoming the difficulties.

There was a considerable amount of diffidence about using spray-painting, no doubt owing to the reasons that the Author gave. He did not feel sure about the Author's reference to improper preparation of the surface, however, because considerable attention was paid to the preparation of the surface, and very few failures had been traced to defects in it. A large amount of the trouble was due to the fact that spray-painting, as first developed, was looked on by everyone as a universal cure for all painting troubles, and many rushed in and adopted it without stopping to think. Spray-painting for the protection of structures—he was not concerned with carriages—had many applications, and in proper hands it gave very economical and adequate protection of the material. There was no doubt that the process and the material had to be carefully controlled, and that was where the Author's work had proved of great value.

In spray-painting, it was essential to use a drier for the air. A recent test with a drier which used calcium chloride as the agent for extracting moisture had shown that the air from the gun was over three times as dry as the atmosphere, and when the paint-supply was disconnected and the jet of air directed on the surface to be painted there was no condensation, whereas without the drier very heavy condensation occurred, and painting would have been absolutely impossible. The test in question had been carried out on a very damp day in November, when the air-temperature was 39° F. and the wet-bulb temperature 38·3° F. Some tests had been carried out earlier in the year, when the temperature of the air was 69° F. and there was not so much moisture present, but a recent inspection of painting then carried out had shown that paint that had been applied with the drier in operation was still perfectly hard and adherent and had a good finish, whereas the surface of paint that had been applied with the drier disconnected from the machine was not really hard; it had wrinkled considerably, and in some cases had become detached and was easily removed by the finger. The tests thus afforded convincing evidence that a drier was essential if spraying were to be used for structural painting. The Author remarked that masks should be used for spray-painting. Strictly speaking, no doubt, that was so, but Mr. McIlmoyle had tried a mask to find out what it was like, and he appreciated very well why the men did not like using it.

The Author stated that the final criterion of any paint was not the result of tests in the laboratory but that of practical tests in service. Like many other users of paint, the L.M.S. Railway received many applications from paint-manufacturers to try out products for which they claimed certain advantages. In the first instance the Paint Laboratory carried out a sequence of tests such as the Author had described, and, if the report indicated that the material might offer any advantages over material already in use, arrangements were made for practical tests to be carried out. Various stations or structures in different conditions were selected and it was generally arranged that one-half of each structure should be painted with the paint under test and the other half with a control paint whose properties were well known, so that the conditions were entirely similar. The results were carefully recorded and expressed numerically, taking separate account of the hiding power, the gloss, the absence of chalking, the absence of checking, and the absence of pitting, and adding the marks. A good paint just applied would be rated at 100, while at the end of its life, when extreme pitting was present, the rating would be between 10 and 20.

Finally, there was the question of cleaning before painting. It was essential that cleaning should be carried out thoroughly, and that painting should follow immediately after the cleaning, before condensation could occur.

Mr. W. H. Peters said he had often wondered why engineers had been so long in coming to the point in giving serious consideration to the question of painting. They had spent thousands of pounds on the examination of other materials—steel, wood, non-ferrous metals and so on —yet they had left a wonderful machine like a railway engine or a railway coach to the foreman painter to finish it off, and often their work had been lost through deterioration. The L.M.S. Railway deserved to be complimented, therefore, on having set up a Paint Research Laboratory.

He had one criticism of the Paper to offer; he did not think that the Author had said nearly enough about the troubles of application. On p. 146, the Author said that he tested proprietary paints and evaluated them. After he had evaluated them, did he use them for his own specifications? On p. 147, the Author said that it required 800 grams of coarse carborundum powder falling through 6 feet to wear away a cellulose lacquer film 0·001 inch thick. At what rate was that film being broken down? On p. 150 the Author mentioned graphite as being injurious in paints because it was liable to promote corrosion. The Author must have had very great experience of corrosion, and Mr. Peters was disappointed that he had not given further information with regard to corrosion-forming pigments. On p. 151, he claimed that turpentine was a better solvent than white spirit for the gums which were used in varnishes. It would be of interest if he would elaborate that conclusion and say how he had reached it. On p. 152 he remarked that cellulose lacquers had proved tremendously popular

or painting motor-car bodies, but had failed on railways. It would be nteresting to know why that was so. On p. 154, he mentioned that ainting time had been reduced by 30 per cent., and he had given some f the reasons for that in introducing the Paper. Perhaps he would say, owever, whether the seven-coat work lasted as long as the seventeen-oat work, or whether repainting was done more frequently than had been he case in the past.

*** **Mr. John Douglas** observed that on p. 159 the Author stated hat painting should not be carried out when the temperature of the tructure was below the dew-point. Could he say whether the amount of ew deposited on a structure varied according to the colour of the paint hich was used, other conditions being equal? It would appear reasonable o expect such a colour as green to encourage a greater dew deposit than he colours at the ends of the spectrum. Had the question been investi-ated, and, if so, what results had been obtained? In the event of ome colours producing a greater amount of moisture than others under imilar conditions, presumably they would be unsatisfactory for use n structures, as the greater amount of moisture deposited would tend to ause more rusting. Similarly, the choice of colour on large surfaces ubject to low temperatures would have some bearing on the amount of noisture present.

Dr. U. R. Evans observed that the Author had given a valuable ractical account of protection by painting. His remarks on the advan-ages of de-scaling were particularly welcome, in view of his practical nowledge of the engineering aspect of corrosion. On p. 157 he stated, Whilst the question of the desirability for complete de-scaling is still a ontroversial one among engineers, gradually, among the scientific in-estigators into corrosion, unanimity is being reached. A most important actor is that the condition of pitting is favoured when the corrosion is ocalized by the presence of a broken film of scale." There was no doubt hat that view was correct. The tests on painted metal organized from ambridge University [1] had indicated very clearly that paint applied o steel covered with a broken film of scale behaved worse than that applied o metal covered with a complete film of scale, which, in turn, behaved orse than paint applied to metal completely free from scale. Almost xactly the same conclusion had been reached in the extensive tests carried

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*** This and the following contributions were submitted in writing. -Sec. Inst. C.E.

[1] S. C. Britton and U. R. Evans, "The Practical Problems of Corrosion." Parts I, VII and IX. Jour. Soc. Chem. Ind., vol. 49 (1930), p. 173T; vol. 51 (1932), 211T; vol. 55 (1936), p. 337T.
K. G. Lewis and U. R. Evans, "The Effect of Mill-scale on the Rising of Paint." hird Report of the Corrosion Committee of the Iron and Steel Institute (1935), 173.

out by Dr. J. C. Hudson for the Iron and Steel Institute,[1] so far as the British climate was concerned (the state of affairs was quite different at certain tropical stations). The facts, therefore, could hardly be questioned. It was not the scale itself that mattered, but the presence of small holes in the scale.

There was no mystery about the causes at work. Electric currents could be detected passing between the scale-covered areas as cathodes and the bare areas as anodes; those currents led to corrosion, and if the bare areas were small compared to the scale-covered areas, the intensity of the corrosion would of necessity be great. The intense corrosion set up at small discontinuities in scale had been demonstrated by experiments on unpainted specimens under suitable conditions[2]; but generally, if no paint had been applied, the corrosion loosened the scale, so that the attack, although localized at first, soon spread out, thus reducing the intensity. If paint had been applied, the lateral extension of the attack was slower, and, under atmospheric conditions, much of the rust was formed below the scale and paint, which were pushed away together, leading to a very serious situation. All those facts had been shown repeatedly by experiments both in the laboratory and in the field; since the electric currents could be demonstrated on the galvanometer, there could be no reasonable doubt about the explanation.

The reasons for the strange persistence of the idea that mill-scale should be left in position on rolled steel before painting might be set down briefly:—

(i) On certain other types of ferrous materials (notably cast iron and probably cast steel), it was advantageous to leave the scale in position; on some types of wrought iron there were two scales, one of which peeled off easily, whilst the other was highly adherent and should be left in position before painting.

(ii) If the paint chosen were a bad one, the results, even on rolled steel, might be less bad if the mill-scale were left in position; obviously, however, bad painting schemes should not be adopted.

(iii) If scale-bearing and de-scaled specimens of steel were both painted and exposed side by side out of doors, the rusting of the de-scaled specimens was frequently more extensive and, to the casual observer, more conspicuous; but on those specimens the rust would stain the paint rather than push it away. The rusting of the scale-bearing steel would usually be highly localized and would tend to loosen the paint; from the practical standpoint, the behaviour of the scale-bearing steel was much more serious, because it would involve pitting and would increase the difficulties of effective repainting; fresh coats of paint applied to unfirm foundations were almost useless.

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[1] Fifth Report of the Corrosion Committee of the Iron and Steel Institute (1938).

[2] U. R. Evans, "Some Aspects of Metallic Corrosion." Trans. Institute of Engineers and Shipbuilders in Scotland, vol. 80 (1937), p. 276.

(iv) The following type of evidence was still frequently advanced ı favour of the plan of applying paint to scale-covered steel. Cases were ell known where identification-numbers had been painted on plates t the mill, and long afterwards those places, where the paint had been pplied to the unbroken scale, had survived, whilst the rest of the surface, hich had been partially weathered before painting, was badly corroded. hat merely illustrated what had been stated above, namely, that partially e-scaled metal behaved worse than wholly scale-covered metal; there as little doubt that complete removal of scale, if combined with a good ainting scheme, gave yet better results. In any case, as he had pointed ut in 1932,[1] other cases were known where the painting of identification-umbers in the early stages had actually caused corrosion instead of pre-enting it.

The apparent disagreement on those points was largely due to confusion etween the "probability of corrosion" and the "conditional velocity." he probability that corrosion might set in within a given period on any ement of area was definitely smaller if the scale had been left on under ıe paint; but, supposing that corrosion had set in on the area at all, it ould, on the average, dig down more rapidly into the metal if scale were resent. Since it was rapid pitting or localized corrosion that led to remature perforation or even to structural failure, it was that form of orrosion that mainly concerned the engineer. It was 5 years since atten-on had been called [2] to the essential difference between the probability f corrosion and its conditional velocity, and to the fact that often factors hich increased the one diminished the other. It would greatly assist ıe reasonable discussion of corrosion-problems if that distinction were more enerally appreciated.

The only serious alternative to the removal of scale was the application efore painting of an inhibitive wash, designed to convert the steel exposed t interruptions in the scale to some substance equipotential with scale, ıus extinguishing the e.m.f. of the cell which was the cause of the localized orrosion. Such washes were being actively developed, especially in merica. They usually contained phosphoric acid, but differed in function om the "panel wash" which the Author recommended for the treatment f scale-free steel. Experience would have to decide whether they were ıfficiently effective to justify the omission of a de-scaling process. It was kely enough that they would increase the life of the first set of paint-oats, but it was not equally certain that they would increase the period etween subsequent repaintings.

Dr. V. G. Jolly observed that the Author's main theme concerned pecifications, testing, application and performance of paints. Those,

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[1] U. R. Evans, "Some Aspects of the Corrosion Problem." James Forrest ecture. Minutes of Proceedings Inst. C.E., vol. 234 (1931–32, Part 2), p. 445.

[2] U. R. Evans, R. B. Mears, and P. E. Queneau, "Corrosion Velocity and orrosion Probability." *Engineering*, vol. 136 (1933), p. 689.

too, were the main concern of engineers when painting had to be done and it might interest them to know something about the outlook of the more progressive sections of the paint industry, which maintained close contact with the railways and studied their requirements. The paint industry (the term "paint" being used to include the whole range of paints, varnishes, enamels and lacquers used as surface coatings) had made great progress during the past decade in the direction of gaining a much better understanding of the scientific basis underlying the manufacture and performance of paint. Having realized the need for scientific research the industry had attracted many skilled investigators who had infused scientific method into a rule-of-thumb industry as far as had been possible. The leading firms maintained testing and research laboratories organized on lines not dissimilar from those described in the Paper. The specifications now commonly issued by important users of paint demanded the attention of chemists who appreciated the significance of the clauses therein and who had sufficient knowledge of raw materials and paint-formulation to enable the production of a paint complying not only with the clauses affecting constitution but also those concerned with performance. Thus it was by no means uncommon in the industry to meet with chemists who were specialists in specification work, and they often maintained close contact with the specifying bodies in order to ensure that there was no misunderstanding regarding the methods by which any paint submitted for test would be evaluated. The wealth of information and experience gained from such work was immediately available for the satisfaction of the demands of the engineer concerned with the initial painting or maintenance of his structures. The question of paint-application and the nature of surfaces and their relationship with durability were also being studied by firms specializing in products for different purposes, and during the past few years the natures of the surfaces of wood, plaster and steel had received increasing attention since the realization that therein lay the reason for many of the paint failures that might erroneously be ascribed to the paint itself.

Dr. Jolly's company maintained a large research laboratory, and quite apart from the investigations relating to new products and the general improvement of existing products, constant attention was given to the important question of the proper treatment of surfaces, which, as the Author had clearly shown, was all-important to ensure maximum service from protective and decorative paint coatings. Such matters as the efficacy of anti-corrosive painting systems on well-cleaned and indifferently cleaned steel surfaces and in different environments, were the subject of careful investigations planned with full cognizance of the results already obtained by The Institution of Civil Engineers and other bodies, in that field. The study of paint application on wood and plaster was pursued on parallel lines to the similar studies of the Research Associations attached respectively to the paint and building industries. The paint manufacture

ad to be prepared to go further than merely to produce a well-tested nd reliable product: he had also to put himself in a position to advise egarding the best conditions for its application, and it was in that border-and that he wanted the co-operation of the engineer.

Mr. W. H. Woodcock asked whether the Author had had any experience ith the more regular and somewhat less troublesome mercury-vapour amp, instead of the arc lamp, for long-period accelerated-weathering ests? Had any tests been developed that would definitely distinguish ynthetic paints with a long life from those that had a fairly short ne? Many synthetic paints were excellent, but others that appeared o be equally good, and had stood up to the tests, had a comparatively hort life.

In his introductory remarks the Author had mentioned the spot test ith acids and alkalies. No information as to their strength was given, ut was it not possible for a paint to fail under that test, and yet in practice o prove to be excellent, provided that it did not come into contact with lkaline or acid conditions?

Had the Author any explanation for the "mild rust-inhibitive effect" f the phosphoric-acid panel wash? In about 1905 Mr. Bertram Blount ad investigated the action of phosphoric acid in producing a lightly-tched surface on steel, preparatory to painting, with special regard to ust-inhibition, and he had found that although an ordinary etched surface asily rusted, the surface produced by etching with phosphoric acid was ore or less passive, the effect being greater than could be accounted for y the minute quantity of phosphorus compounds left on the surface. n equally passive surface was obtained by etching with an acid solution f chromic acid.

The Author, in reply, suggested that the Sea-Action Committee's experi-nce (referred to by Mr. Wilson) of finding spray-painting unsatisfactory ight possibly have been due to incorrect formulation of paints used for praying. It had to be appreciated that the full possibilities of spray-ainting could only be developed after due consideration of the paints to e employed, which had to possess certain properties not commonly met ith in brushing-paints. The remark made by Mr. Wilson regarding the anner in which exposure-tests were carried out to ascertain the effects of a-water and sea-air at Southampton and Weston-super-Mare were very teresting, but it should be appreciated that time was an essential feature f routine tests for paint-control, and that what was obviously needed was ome accelerated method which would give reproducible results comparable ith those obtained after extended natural weathering.

Dr. Jordan's remark that "it did not matter so much what was in the n as what was done with it" emphasized a point which could with lvantage be more fully considered by those engaged in industrial painting. lthough considerable scientific effort had been put into the production f modern protective and decorative coatings, little effort had been made

on the part of users to study conditions of application, and so to bring out the full value of improved painting materials.

The point raised by Mr. Pugson regarding the corrosion at the edges of panels round the windows of railway carriages was one which had received considerable attention recently, and it was felt that a solution to the trouble might shortly be found entailing an acid-resisting material as a jointing composition, to overcome the ravages of the acid-solutions which were employed in the cleaning of carriages running in service. At the same time it had always to be appreciated that, where abrasions on paint were caused through scrubbing with brushes, it was very difficult to provide any adequate treatment which would overcome corrosion-problems at those points.

The use of paints containing latex as well as chlorinated rubber had been under review in the Laboratory, and some encouraging results had been obtained, particularly with the chlorinated-rubber paints. The tensile-strength test of 100 lb. per square inch for rubber paints which was mentioned by Mr. Lloyd did not compare very favourably with the results obtained on various types of organic coating materials. The range of tensile strengths obtained was between 500 and 3,000 lb. per square inch.

The remarks made by Mr. McIlmoyle brought out the point that the observation of a " close season " for exterior painting had certain difficulties, but it was important to realize that paint applied under bad atmospheric conditions could not be expected to give the results that would be obtained if the paint were applied under more suitable conditions. The employment of casual labour, as was implied in the seasonal engagement of painters (especially where supervision was difficult, as on the railway) was a dangerous practice, and other methods of reducing the painting of completely exposed surfaces during the winter should be explored. The preparation of surfaces for painting did not, in general receive the attention commensurate with its importance, and he was inclined to doubt whether Mr. McIlmoyle's information regarding the number of occasions on which paint-failures had been due to incorrect preparation was really reliable. Mr. McIlmoyle's observations with regard to spray-painting revealed an approach to the problem which should do much to establish that method of application. It was equally important to realize the limitations of the method as it was to appreciate its manifold advantages. The details of the method of testing the durability of paints were interesting, but it had the limitation that it was not possible to apply the result of any test to future supplies, and it was there that the laboratory-tests were indispensable.

It was impossible to cover the whole wide field of paint technology in a single Paper, and Mr. Peters' criticism of the Paper was one which followed from that; the particular aspect of the subject which Mr. Peters appeared to think had received meagre reference might well form another Paper

Vith regard to the statement contained in the Paper relating to the timulative effect of graphite on the corrosion of steel, it should be mphasized that that characteristic was noticeable only when the pigment vas used in a priming paint; when incorporated in a finishing paint raphite was a very valuable pigment. Other pigments which stimulated orrosion when employed in priming paints included lamp-black and earth igments containing water-soluble sulphates. The superiority of the olvent properties of turpentine had been discussed so often that there vas no point in repeating the evidence, but long experience had confirmed he view given in the Paper. The extreme conditions to which railway ehicles were subjected, the drastic cleaning necessary, coupled with the ractice of stabling the vehicles on exposed sidings for protracted periods, ad the effect of rendering unsuitable for exteriors of railway carriages the ellulose lacquers which had been used with so much success in the finishing f motor-cars.

Mr. Douglas raised an interesting point in connexion with the effect f colour on the deposition of dew on structures. No experiments had et been conducted to determine that fact accurately, but it was expected hat other factors, such as the accumulation of dirt, and surface-condition, vould have a far greater effect.

Dr. Evan's observations would be regarded as a valuable contribution o the discussion on the Paper, and nothing could be added to the lucid xposition of the mechanism of corrosion, and of the exact part played y mill-scale. His reference to the American washes of the type of the ' panel wash " referred to in the Paper had been the subject of experinents in the Laboratory, but the experiments had not proceeded far nough to enable any expression of opinion to be given. It should be ointed out, however, that those American inhibitive washes also contained hromic acid.

The remarks made by Dr. Jolly in respect of the change of outlook of he paint industry gave confirmation to the view expressed in the Paper. The value of the specifications could only be realized where close technical o-operation between the user and the manufacturer existed. Dr. Jolly vould agree that the intervention of the paint technologist had been ttended by the most satisfactory results, since he had been able to express n terms understandable by both the paint manufacturer and the engineer he exact requirements of the latter.

Opinion was still somewhat divided on the question of the use of nercury-vapour, as compared with carbon-arc, lamps for accelerated-veathering devices, but the relatively steady rate of emission of the ctive rays, as well as the closer approximation of the distribution of the vave-lengths of the light emitted by the carbon arc to those of the sun, onfirmed the Author's view that carbon-arc lamps were really the more atisfactory. The " weatherometer " which had been used in the Laboraory had formed a valuable sorting test for synthetic-resin paints, and the

answer to Mr. Woodcock's question was therefore that the distinction between good and bad synthetic-resin paints could be made by that machine. With regard to Mr. Woodcock's question in respect of the tests for acids and alkalies, that was only introduced where the paints would come into contact with those agents, either as an atmospheric pollution or in the cleaning solutions which were used during the life of the paint. A simply-stated explanation of the "mild rust-inhibitive effect" of the phosphoric-acid panel wash was that it was due to the formation of a film of insoluble phosphates on the surface of the metal.

*** The Correspondence on the foregoing Paper will be published in the Institution Journal for October, 1938.—Sec. Inst. C.E.

ORDINARY MEETING.

26 April, 1938.

SYDNEY BRYAN DONKIN, President,
in the Chair.

It was resolved—That Messrs. F. H. Brunt, S. W. Budd, Robert Chalmers, J. D. C. Couper, D. C. Farquharson, A. S. Grunspan, R. W. Mountain, P. G. Smales, P. J. H. Unna, and R. W. Weekes be appointed to act as Scrutineers, in accordance with the By-laws, of the ballot for the election of the Council for the year 1938–39.

The following Paper was submitted for discussion, and, on the motion of the President, the thanks of The Institution were accorded to the Author.

Paper No. 5174.

"Southampton Docks Extension."†

By MALCOLM GORDON JOHN McHAFFIE, M. Inst. C.E.

TABLE OF CONTENTS.

INTRODUCTION.

THE works described in this Paper are those recently carried out by the Southern Railway Company at Southampton in what was formerly known as the West bay of the river Test, extending from the Royal Pier to Mill-brook Point. Upon reference to Fig. 1, Plate 1, it will be seen that the Eastern and Western estates are separated by waterside property belonging to the Southampton Harbour Board, who also own and manage the Town Quay and the Royal Pier. There is, however, rail and vehicular road connexion between the two estates, and all rail sidings are connected to the Southern Railway system.

In the original lay-out, consideration was given to two schemes for the berthing of ships, the first alongside a straight quay-wall running from end to end of the site, and the second alongside five large jetties projecting out into the river Test in a north to south direction. The advantages of the first appeared to be outweighed by those of the second, and it was decided to adopt the latter. Upon the recommendation of the late Sir Frederick Palmer, K.C.M.G., C.I.E., Past-President Inst. C.E., this decision was reversed, and the straight quay as shown in Fig. 1, Plate 1, was adopted. The position of the quay has been arranged so as to permit the future provision of a jetty about 4,500 feet long by 400 feet wide, 600 feet away from, and parallel with, the quay-wall. Space has been reserved at the western end of the new estate for the future provision of another graving dock alongside that already built.

† Correspondence on this Paper can be accepted until the 1st September, 1938.—SEC. INST. C.E.

The reclaimed land has a frontage to the river Test of about 2 miles, ıd a depth of about ⅓ mile; the area is 407 acres, of which roughly ıe-quarter belongs to the Southampton Corporation.

The works will be described under the following headings:—

Works between the Town Quay and the Royal Pier.
Dredging and reclamation.
Quay-wall.
King George V graving dock.
Condensing-water culverts for the Corporation electricity-station, and storm-water drainage.
Subsidiary works, comprising:—
- Passenger and cargo sheds.
- Carriage-cleaning and warming shed.
- Railway sidings.
- Vehicular roads.

Throughout the Paper and in the illustrations, the levels given refer to ock datum, which is 100 feet below dock standard cope, and 87·75 feet elow Ordnance datum (Liverpool). The tidal range is 13 feet, H.W.O.S.T. eing at a level of 94·00 and L.W.O.S.T. at a level of 81·00.

Works Between the Town Quay and the Royal Pier.

To provide rail connexion between the Eastern and Western estates, he previously existing arrangement of sidings in the vicinity of the Town)uay and Royal Pier had to be remodelled, and, in order to obtain adequate pace for this to be done, it was necessary to reclaim a strip of land between he Town Quay and Royal Pier. Accordingly, a new retaining wall, 20 feet long, was built about 100 feet in front of an existing quay-wall nd the intervening space was filled up with dredged material. The rail onnexion also involved the demolition of the former toll-house at the ntrance to the Royal Pier and the building of another in substitution.

The new retaining wall is shown in cross section in *Fig. 2*, p. 186. It onsists of T-shaped reinforced-concrete "Ravier" piles, anchored back by inged reinforced-concrete ties.

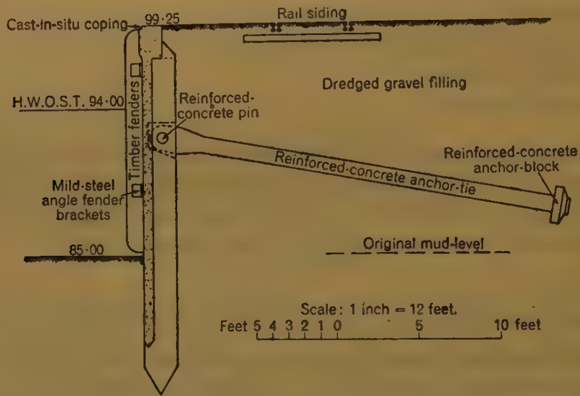
Dredging and Reclamation.

The formation of the approach-channel and the two swinging-areas one opposite each end of the quay-wall) involved deepening the bed and he mud-flats on the left bank of the river Test from an average of about feet to a depth of 35 feet below L.W.O.S.T. The dredging was done by ucket-ladder dredgers. The total quantity removed was 16,450,000 ubic yards, measured in situ, of which 6,680,000 consisted of soft mud nd peat, 3,500,000 of gravel and 6,270,000 of sandy clay. The soft mud

and peat were taken to sea in hopper-barges and dumped; the gravel wa[s] used for the reclamation-banks and for concrete aggregate; and the sand[y] clay was taken in solid-bottom barges alongside stationary pumping vessel[s] and pumped ashore through 24-inch-diameter pipe-lines for reclamation.

The reclamation was carried out in two stages, divided by a cross bank built at right angles to the quay-wall, and situated approximately mid-way along the length of the area to be reclaimed, as shown in *Fig. 3*. Th[e] first and second stages of reclamation were eastwards and westwards of th[e] cross bank respectively.

Fig. 2.



QUAY-WALL BETWEEN TOWN QUAY AND ROYAL PIER.

Preliminary Reclamation-Works.

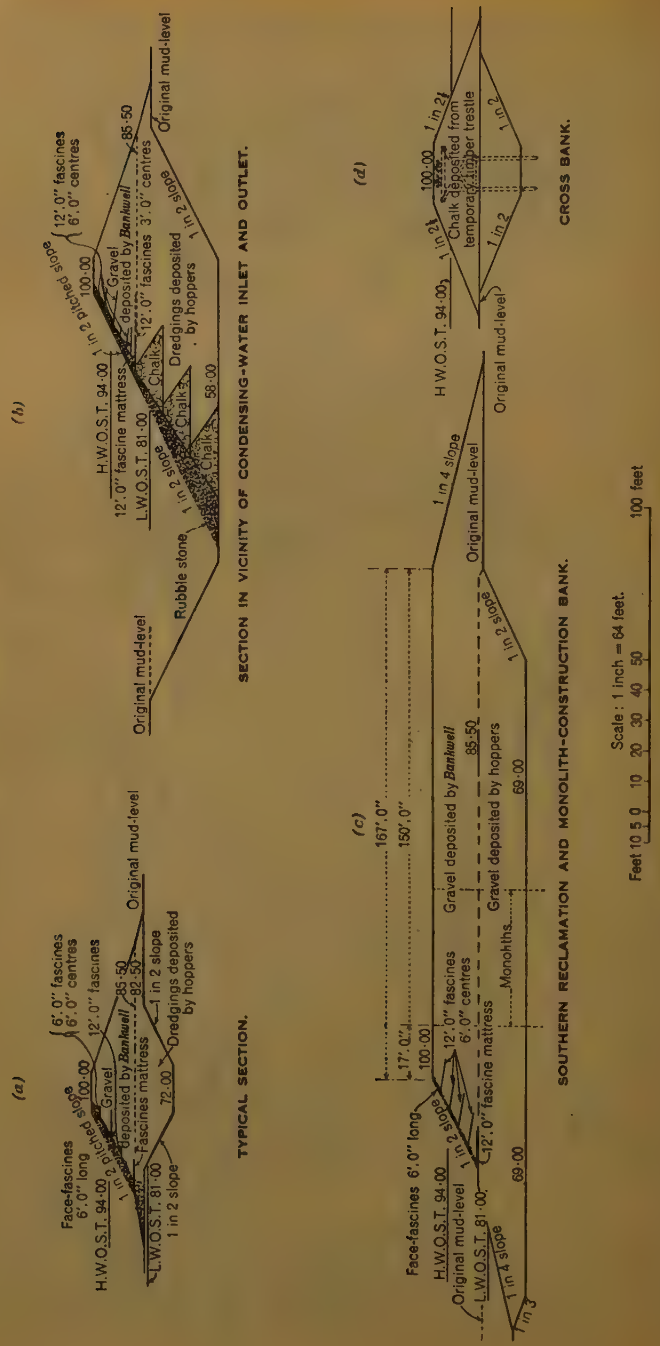
Upon reference to *Fig. 3* it will be seen that landward of the forme[r] high-water mark of ordinary tides, practically no dry ground was availabl[e] for use as contractors' yards; the first requirement, therefore, was t[o] reclaim a preliminary area, roughly triangular in shape and about 18 acre[s] in extent, at the eastern end of the bay. The southern embankment fo[r] this area (now forming the seaward side of land belonging to the Corporation which they propose to lay out as a recreation ground) commenced at th[e] Royal Pier and proceeded westwards for a distance of 1,000 feet, an[d] thence northwards to the old foreshore. In addition to providing space fo[r] contractors' yards, the reclamation of this area was intended to test th[e] practicability of constructing the enclosing banks with gravel obtaine[d] from the dredging operations.

A typical section of the bank westwards of the Royal Pier is shown i[n] *Figs. 4* (*a*), p. 188. Along the line of the bank the mud was dredged awa[y] in the form of a channel with a bottom width of about 15 feet, exposin[g] the underlying gravel stratum. Firm dredged material was then deposite[d]

Fig. 3.

SITE OF DOCKS EXTENSION BEFORE WORKS WERE COMMENCED.

Figs. 4.



TYPICAL SECTION.

SECTION IN VICINITY OF CONDENSING-WATER INLET AND OUTLET.

SOUTHERN RECLAMATION AND MONOLITH-CONSTRUCTION BANK.

CROSS BANK.

Scale: 1 inch = 64 feet.

Feet 10 5 0 10 20 30 40 50 100 feet

RECLAMATION-BANKS WESTWARD OF ROYAL PIER.

y small hopper-barges to a height of about $4\frac{1}{2}$ feet above L.W.O.S.T. onstruction above this level was carried on by means of a vessel consisting f two pontoons spaced 23 feet 7 inches apart, the space being bridged by n overhead steel structure carrying a bucket-ladder elevator and a rojecting arm equipped with a travelling rubber belt. Barges containing redged gravel were towed into the space between the two pontoons, and ere unloaded by the bucket-ladder elevator into an overhead hopper rough which the gravel passed to the travelling belt, whence it was eposited in the bank. Frequently the output from the vessel, named the *ankwell*, was over 3,000 cubic yards (barge measurement) per day of 4 hours.

The seaward side of the bank was temporarily protected by brushwood scines. This protection was commenced with a fascine mattress 12 feet ide along the toe at a level of 85·50, and above this level the face-fascines ere tied into the bank by single fascines placed 3 feet apart vertically and feet apart horizontally. All the fascines were well pegged down into the ravel with forest pickets. In the vicinity of the site of the intake and utlet of the condensing-water culverts it was necessary for the foundation f the bank to be taken down to a level of 58·00; the section of the bank that vicinity is shown in *Figs. 4* (*b*). Subsequently the seaward face of e bank, being permanent work, was pitched with rubble stone.

irst- and Second-Stage Reclamation-Works.

The method of bank building described above having proved efficient nd economical, an adaptation of it was adopted for the main reclamation-ank, through which the monoliths forming the new quay-wall had to be ink; it was made 167 feet wide on top to accommodate the contractors' rane-tracks and works railways, and is shown in cross section in *Figs. 4* (*c*). fter the monoliths had been sunk that portion of the main bank in front f them was dredged away.

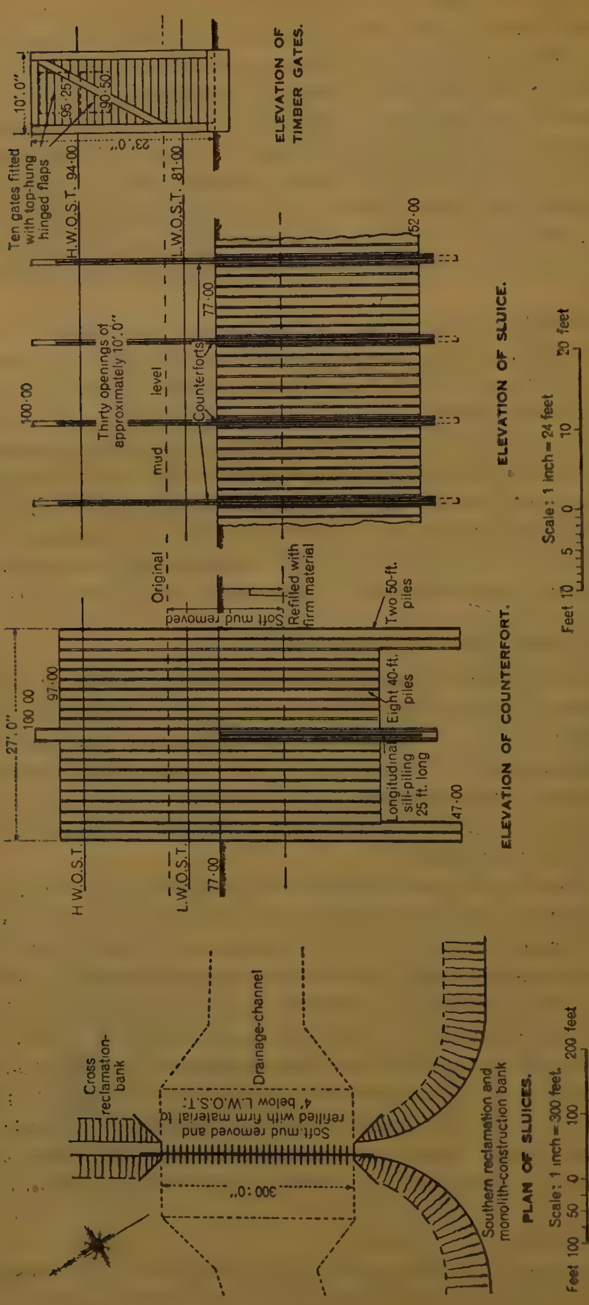
It was found by a model that the velocity of water, whilst the first-age reclamation area was still tidal, might scour away the back of the ain bank during the fast ebb of a spring tide, and to meet this con-ngency a drainage-channel, about 6 feet deep and widening from 50 feet at s eastern end to 150 feet at its western end, was dredged behind the main ank; the western end of this channel is shown in *Figs. 5*, p. 190. A similar rainage-channel was provided in the second-stage reclamation-area.

Along the line of the cross bank a channel was dredged, as previously escribed, into which firm dredged spoil was dumped from hopper-barges. temporary timber trestle was then constructed from which chalk was ast out from railway wagons. A section of this bank is shown in *Figs. 4* (*d*).

emporary Sluices.

The construction of the main bank preceded that of the cross bank, so at, until closed by the latter, the area of the first stage of reclamation

Figs. 5.



TEMPORARY SLUICES IN CROSS RECLAMATION-BANK.

ras tidal. It was realized that a critical point would be reached when he velocity of the current through the gradually decreasing gap between he two would be sufficient to scour away the end of the cross bank and he back of the main bank opposite to it. In order that the banks should ot be eroded it was considered that the velocity of tidal flow should not xceed 3 miles per hour; calculations showed that a gap 300 feet long rould suffice to keep the flow within that limit at any state of the tide, nd it was therefore decided to construct the temporary sluices shown in *'igs. 5.*

Along the length to be occupied by the sluices, and for a width of 100 eet, the soft mud was dredged away, and clay was dumped from hopper-arges thereon to a level of about from 78·00 to 80·00; this was sub-equently levelled off to 77·00 by re-dredging.

A sill of steel sheet-piling in 25-foot lengths was then driven along the entre-line of the sluices, the top being left at a level of 77·00. At right ngles to the sill twenty-nine counterforts composed of 40-foot and 50-foot teel sheet-piles were driven at intervals of 10 feet, the tops finishing at level of 97·00; the junctions between the counterforts and the sill were ffected by special cruciform piles 50 feet long. Wing-walls of steel sheet-iling were driven at each end of the sill, and were connected to it by pecial junction piles; the wing-walls were anchored back into the banks t either end of the sluice.

Framed timber gates were constructed to slide into the recesses of the ruciform piles, each one being specially fitted to its sill. Ten of the gates vere provided with two openings 5 feet wide by 3 feet 9 inches high, he sill of the lower openings being at a level of 90·50 (that is, at the level f high water, neap tides), and that of the upper openings being at 95·25; he openings were fitted with top-hung hinged flaps, arranged to open utwards, thus permitting a discharge of water from the area to be eclaimed without permitting ingress of water to the area during high tides. After being fitted one by one in their respective positions the timber ates were stored on the adjoining banks, and when everything was in eadiness they were all dropped into place during one period of low water t neap tides. Chalk was then deposited on either side of them up to the evel of high water of neap tides as quickly as possible in order to strengthen he whole structure.

Although the dropping of the sluice doors into place was expected to be arried out according to programme (as indeed it was) there was a possibility hat the chalk would not be deposited on either side before the following pring tides. In view of this possibility, two extreme cases of pressure on he gates required consideration, namely :—

(1) With the level of impounded water inside at about 6 inches above the sill of the lower openings (that is, at a level of 91·00), with water at L.W.O.S.T. on the outside.

(2) With the level of impounded water inside at 90·50 with water at extraordinary H.W.S.T. (that is, at a level of 96·00) on the outside.

In each case the lateral pressure to be resisted amounted to about 26 tons, the resultant in case (1) being at a level of 82·00, and that in case (2) being at 85·20.

As no data regarding the strength of steel sheet-piling in a longitudinal direction appeared to be available, and as it was a practicable impossibility to calculate with any degree of accuracy the behaviour of the counterforts under load, it was decided to ascertain this, as far as possible, by test.

Tests on Counterforts.

It was considered that the counterforts might fail either by sliding, overturning, or buckling. The test was therefore designed so that:—

(*a*) a lateral pull greater than 26 tons could be applied in order to test resistance against sliding;

(*b*) a moment could be applied greater than that which might be produced in either case (1) or case (2) above, in order to test the resistance against overturning, the test load being applied at a level of 90·50;

(*c*) observations could be made for any sign of failure of the counterfort by buckling or otherwise.

An additional counterfort was accordingly driven in line with that to be tested, a gap of about 12 feet being left between them, as shown in *Fig. 6*. The function of the additional counterfort was solely to serve as an anchorage from which a pull could be exerted on the counterfort to be tested.

As there was about ¼ inch play in the clutches, it was thought that excessive deflexion, or possibly failure, might arise through the piles sliding in the clutches when the load was applied. To resist this shearing effect it was considered that diagonal ties might be necessary; in designing these ties it was assumed that all piles were pin-jointed at ground-level and that half the shear only would be taken up by the friction of the piles in the clutches; upon these assumptions it was found that 1¼-inch bars might be necessary. In the additional counterfort the ties, together with the 12-inch by 12-inch walings, were tightened up, but in the counterfort to be tested the ties were left slack, as it was thought the test might show them to be unnecessary; actually this proved to be the case.

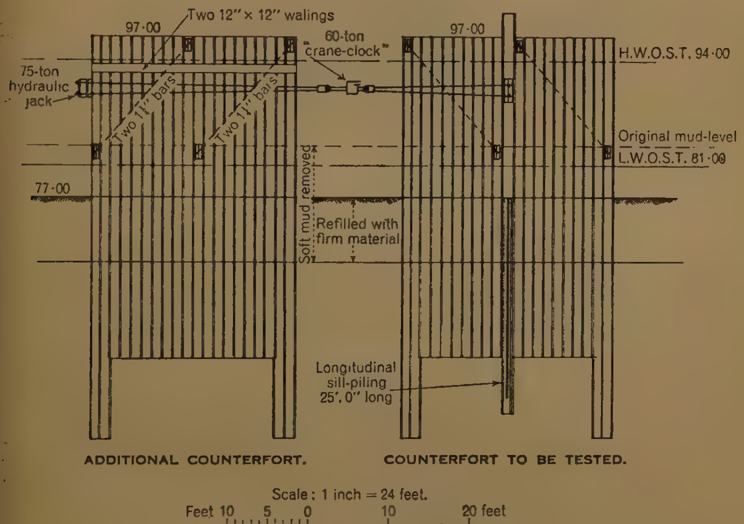
The pull was effected by means of a 75-ton hydraulic jack at one end of the additional counterfort, and was transmitted to the counterfort to be tested by four 1½-inch steel bars, a 60-ton "crane-clock" being placed between the two counterforts to register the increments of load.

The test proceeded until a load of 45 tons was registered, when the flange of the pile against which the hydraulic jack was resting buckled.

The loads equivalent to case (1) and case (2) compared with the test-load as follows :—

	Force.	*Moment.*
Case (1).—Tide-level at L.W.O.S.T. .	25·7 tons.	231·3 tons-feet.
Case (2).— „ „ „ E.H.W.S.T. .	25·3 „	311·5 „ „
Maximum test-load applied. . . .	45·0 „	787·5 „ „

Fig. 6.



Testing of Counterforts.

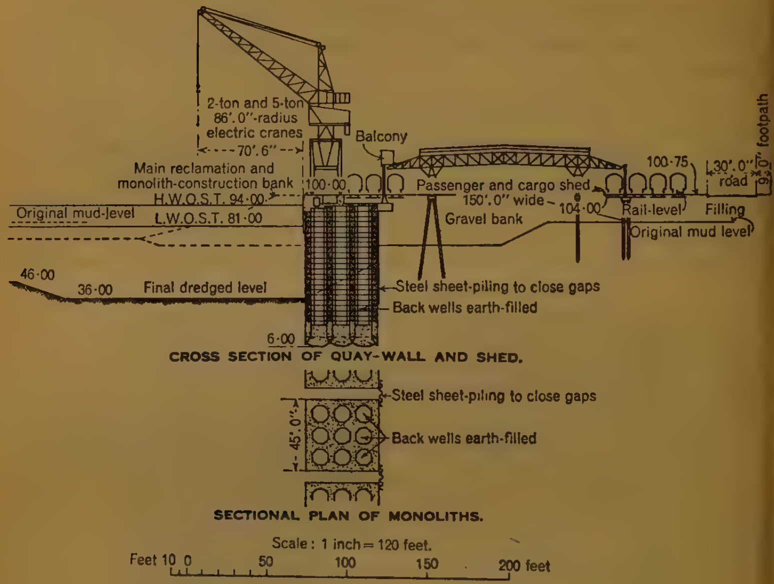
A permanent horizontal deflexion of 1·4 inch was observed in the counterfort under test. Neither of the counterforts showed signs of buckling under the load.

Quay-Wall.

Construction.

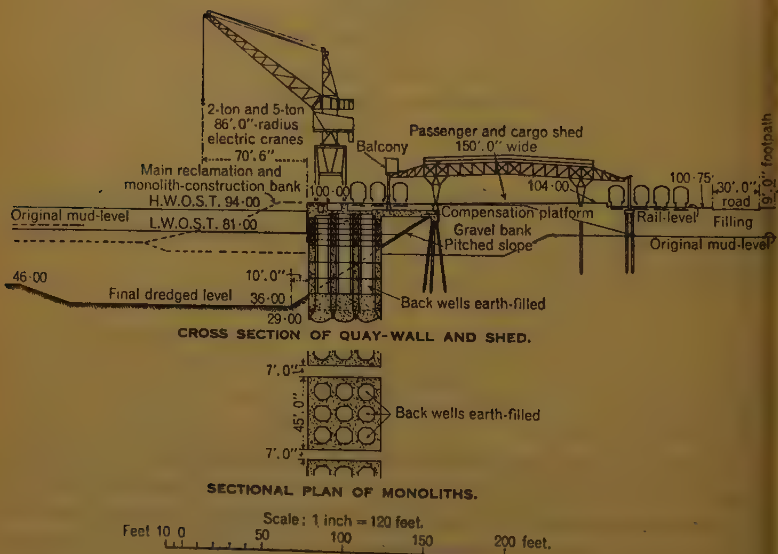
The quay-wall has a total length of 7,542 feet and is shown in cross section in *Figs. 7* and *8* (p. 194). For 7,050 feet of its length it has been designed for a depth of water of 45 feet alongside at L.W.O.S.T. It consists of one hundred and forty-six monoliths, each 45 feet square in plan and having nine octagonal-shaped wells measuring 10 feet 4 inches across the flats.

Figs. 7.



MONOLITH QUAY-WALL AS ORIGINALLY DESIGNED.

Figs. 8.



MONOLITH QUAY-WALL AS MODIFIED.

Γhe outside and cross walls were 3 feet 6 inches thick. The first seventy-ight monoliths at the eastern end, comprising the first stage of the work, vere spaced 4 feet apart, and the remaining sixty-eight, comprising the econd stage, were spaced 7 feet apart. The shoes, which are shown in *Fig. 9*, p. 196, weighed about 34 tons each; they were 5 feet 6 inches high nd consisted of steel plates riveted to angles. To strengthen the cutting dge an 8-inch by ½-inch bulb plate was introduced between the outside nd cant-plates.

The shoes were delivered to the site in sections, and were erected n the gravel embankment previously described, where the site-riveting was erformed. The bases of the monoliths were formed in reinforced concrete, n and above the shoes, to a total height of 15 feet 6 inches above the utting edges; above the bases construction was continued in concrete lockwork, rising three courses to 10 feet.

When the reinforced-concrete bases had been formed, they were unk by means of grabs operating in the wells until their tops were level vith the surface of the embankment; three courses of blockwork were hen built and sinking operations were renewed. Building and sinking in ifts of 10 feet were thus continued until the monoliths had reached the lesired depth. As the result of experience in the first-stage monoliths it vas considered advantageous to substitute in-situ concrete for the lower welve courses of blockwork, and this procedure was adopted in the second tage of the work.

Grooves were provided in the tops of all blockwork courses throughout he outside and cross walls for the reception of 1-inch-diameter steel einforcing-bars, whilst 1½-inch-diameter steel reinforcing-bars, securely astened inside the shoes, were carried up through the courses at the unction of all walls.

After sinking, the bottoms of all wells were carefully cleaned up and a oncrete seal, about 13 feet deep, was deposited through the water in oxes; the three back wells were then filled with earth.

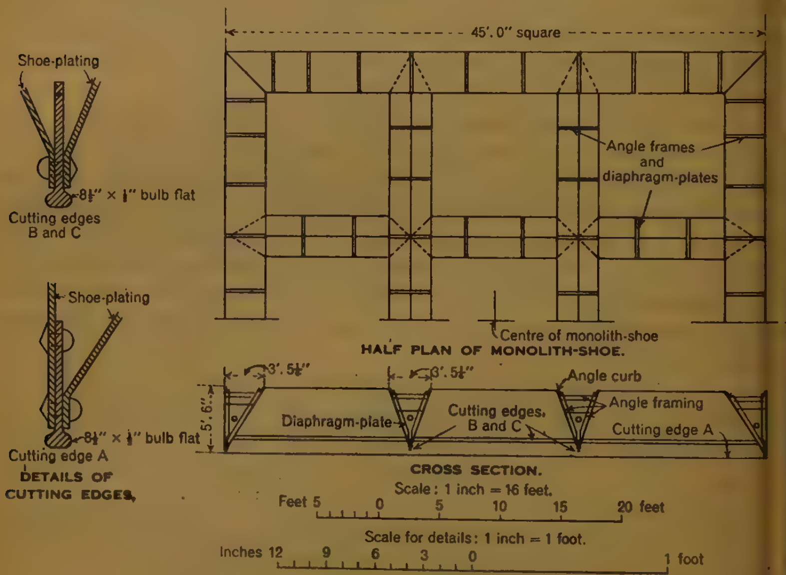
The construction of the superstructure, consisting of concrete covers ver wells and gaps, cope-work, pipe-culvert and back crane-beam, was leferred until after the dredging in front of the wall had been done, in rder that any "pitching" which might occur to the monoliths should ot damage the superstructure.

The original design provided for the monoliths to be sunk to a level of ·00, or to 30 feet below dredged level, but considerable difficulty was ncountered in attaining this object. Sinking through the first 30 feet of ravel embankment was comparatively easy, the weight of the monoliths hemselves generally being sufficient to carry them down without the aid f much kentledge.

Below the gravel embankment sinking and control presented many lifficulties, especially in a bed of firm greensand. Examination by diver evealed the fact that the ground at the bottom of the wells was dished to

roughly hemispherical shape, and that the cutting edges were supported on walls of earth under the cant-plates which the grabs were unable to reach. Heavily loading the monoliths with kentledge in the form of large cast-iron blocks was the usual method of weighting them while being sunk, and in addition the wells were dewatered by pumps in order to reduce the flotation. The dewatering had to be done with great care, as it tended to cause blows in the wells, which, while helpful under certain circumstances in the earlier stages of sinking, were fraught with risk in the later stages.

Figs. 9.



Steel Monolith-Shoe.

After trying various methods, two appliances made upon the site were eventually employed with signal success. The first, known as a "scarifier," consisted of a number of vertical 15-inch by 15-inch steel I-beams riveted to form a framework octagonal in plan and of such dimensions that the appliance could pass down the wells with a small clearance all round. The appliance weighed about 10 tons. The other appliance, known as a "surger," was somewhat similar in design, but had the vertical steel I-beams around the outside only, a 1-inch thick horizontal diaphragm-plate being provided, with a 3-foot square hole in the centre. The function of the "scarifier" was to pound up the firm sand into such a condition that the grabs could easily excavate it, and to this end the "scarifier" was alternately raised by a crane and allowed to drop freely through several

eet into the bottoms of the wells. The operation of the "surger" was imilar, the effect being that the walls of earth under the cutting edges ere worn down by the surge of the water in the wells.

Several of the earlier monoliths were found to be damaged to a lesser or reater extent as the result of the sinking difficulties, and in these all the ells were filled with mass concrete. It was found that very little or no amage occurred before the shoes reached a level of 29·00, or 7 feet below redging level, and it was therefore decided to limit the sinking of the emainder of the monoliths to that level, and to compensate for the loss of tability thus incurred by removing the gravel behind and forming it to a lope of 1 in 1½. The triangular void thus formed was covered by a ontinuous reinforced-concrete slab, 4 feet 6 inches thick, one side of which ested on the back walls of the monoliths and the other on reinforced-oncrete piles. The tops of the latter, together with those for the shed-oundation, were incorporated in a continuous capping beam. This onstruction, which is shown in *Figs. 8* (p. 194), was adopted from monolith Io. 15 to monolith No. 146.

The ground between the monoliths was allowed to assume a natural lope, and its surface, with that of the 1-in-1½ gravel slope, was cloaked ith rubble limestone for a thickness of about 3 feet. In the earlier tages, where the wall had a full backing of earth behind, the gaps between he monoliths were closed by heavy-section steel sheet-piling; from ionolith No. 15 westwards, where the gravel slope was formed, the gaps ere not closed.

uantities.

Amongst the principal quantities dealt with were :—

1,000,000 cubic yards of excavation;
600,000 cubic yards of concrete;
8,500 tons of reinforcing steel;
5,000 tons of steel in monolith-shoes.

uay Cranes.

The quay is equipped with twelve 5-ton and sixteen 2-ton portal level-iffing cranes, all operating at 86 feet radius. The crane-gauge is 18 feet.

The 5-ton cranes have electric floating-brake control on the hoist-iotion. The speeds are :—

Hoisting	100 feet per minute.
Travelling	50 ,, ,, ,,
Luffing	120 ,, ,, ,,
Sluing	0·9 revolution per minute.

They can lift 2½ tons at 200 feet per minute.

The 2-ton cranes are of the free-barrel type with contactor operatio
for the hoist-motion. The speeds are :—

Hoisting	200 feet per minute.
Travelling	50 ,, ,, ,,
Luffing	160 ,, ,, ,,
Sluing	1·1 revolution per minute.

Cable-Culvert.

A culvert for the accommodation of electric cables, water-mains, etc
is provided as shown in *Figs. 7* and *8* (p. 194).

King George V Graving Dock.

The graving dock is shown in Figs. 10, 11, 12 and 13, Plate 1. Th
dimensions are as follows :—

Length	1,200 feet.
Width at entrance and between buttresses	135 ,,
Depth from coping to floor	59 ,,
Depth from coping to sill	$56\frac{1}{2}$,,
Water over blocks at H.W.O.S.T.	$48\frac{1}{2}$,,

The side walls have a base and top width of 30 feet and 10 feet respectively
They have a front batter of 4 to 1 with a toe in the form of six low-leve
altars. For a length of about 570 feet along the middle of each wa
a further altar is provided at level 85·50, but otherwise no altars have bee
provided, as, following the accepted practice of docking large ships, no sid
shores are used, the vessel resting on a "cradle" formed by the keel
and bilge-blocks. Four buttresses have been formed in each side wall t
keep the bilge-keels of vessels away from the battered walls and the low
level altars; the upper portions of the buttresses are solid-fendered wit
English elm.

Three culverts have been formed in each side wall, one 4 feet in diamete
for floor-drainage, one for the salt-water fire-main (which will be referre
to later) and one in which are accommodated fresh-water mains, electri
cables, etc.

The head wall is segmental in plan, and has a base and top width o
24 feet and 8 feet respectively. The floor is 25 feet thick at the centre
diminishing in the form of an inverted arch to 20 feet at the sides. Th
surface of the floor has a fall of 6 inches from the centre to the two open sid
drains, which communicate with the 4-foot-diameter culverts in the walls
The culverts, in turn, communicate with the large filling and emptyin
sumps in the floor near the entrance.

Dock-Construction.

The construction of the dock was carried out in the dry. The sit
was bounded on the north by the original foreshore, and on the east by

previously-constructed bank, along the site of which the mud had been dredged away, the channel thus formed having been filled with firm dredged material and the bank completed with chalk cast out from railway wagons standing on a temporary timber trestle. This bank was continued in a similar construction, and concurrently another bank was commenced from the original foreshore at Millbrook Point by depositing gravel in a dredged cut by the special bank-building machine previously described on p. 189; the seaward face of the latter bank was temporarily protected by brushwood fascines, and subsequently by stone pitching. The two banks met at the east and west ends respectively of a sluice-opening 100 feet long. The sluices consisted of steel sheet-piling, with wing-walls and sill provided for the same reason as, and in a similar manner to, those previously described on p. 191, except that none of the framed timber doors were provided with openings.

The doors were dropped into position at low water of a spring tide and chalk and gravel were cast out on either side of them as quickly as possible; simultaneously the pumping out of the enclosed area was commenced. The enclosed area was somewhat larger than was necessary for the actual construction of the dock, but it contained the gravel bed which ultimately supplied a large proportion of the concrete aggregate required for the dock; furthermore, when the gravel had been salved the enclosed area formed a valuable and convenient tipping site for the dock-excavation.

In order to reduce, as far as possible, the percolation of tidal water into the enclosed area whilst the dock was under construction, a continuous wall of steel sheet-piling was driven along the line of the enclosing bank and the original foreshore. Trial borings along the line of this piling were made, and the lengths thereby so arranged that everywhere the piling passed through the underlying stratum of natural gravel and about 5 feet into the sandy clay beneath. The leakage from the tide was at first considerable, but after a few days it was approximately 7,000 gallons per minute, gradually becoming less until at the end of a further 10 weeks it was approximately 1,800 gallons per minute, and remained at about this figure during the whole time the works were in progress.

While the bank-construction was going on a dredger was employed in removing soft mud from the area to be enclosed until such time as the gap between the advancing bank-construction from the east and from the west had been reduced to a width only sufficient for the dredger to pass out. As soon as the bank was closed and pumping commenced, two steam navvies were employed to remove the mud from the remainder of the enclosed area; this mud was tipped from a jetty, specially constructed for the purpose, into hopper barges, by which it was taken to sea and dumped. The jetty was later utilized for unloading dredged gravel to supply the balance of concrete aggregate required for the dock-construction.

Gravel-excavation was commenced as soon as the dock-area had been

cleared of mud, the material being stored in a dump nearby until suc time as concreting could be commenced; thereafter gravel was excavate at the rate required for the concrete-mixers. Trench work was com menced as soon as possible at the entrance, so that the construction of th walls of the caisson-camber and the east wing-wall, together with the fillin behind them, could be co-ordinated with the construction of the west en of the monolith quay-wall, and also so that the culverts and pumpin station could be proceeded with as rapidly as possible. The side walls wer constructed in timbered trenches, the "dumpling" between them bein subsequently removed by dragline excavators. As much excavate material as practicable was tipped inside the enclosed area, the balanc being tipped along the foreshore near Millbrook station.

The toes of the side walls were formed to a skewback normal to the lin of thrust from the inverted arch of the floor, the latter being formed in thre large voussoirs across the width of the dock. Concreting in each of th voussoirs continued uninterruptedly, including the floor-surface, in ord to eliminate horizontal joints. So as to maintain as much support to th toes as possible, dragline excavation of the "dumpling" was only allowe to proceed ahead sufficiently far at a time to allow shutters for the nex series of voussoirs to be erected. The bottom altars were not formed a the same time as the side voussoirs owing to the complicated nature of th shuttering which would have been required, and their construction wa allowed to lag behind the floor concreting to the extent of two voussoir The concreting of the side walls was temporarily suspended when they ha reached a level of 60·00, until the floor-concrete was sufficiently fa advanced. This was in order that, in the event of any tendency for th walls to settle, the thrust from the skewbacks should be transmitted to th floor-arch.

Concrete for the mass-work was mixed at a central plant situated on th former foreshore near the head of the dock. This plant combined th operations of gravel-washing and concrete-mixing, and was capable of a output of 2,000 cubic yards per day. The bulk of the concrete was mixe in the proportion of 1 to 6, with a facing in the walls of 1 to 4 concret 12 inches thick, both mixes being placed at the same time to obviate vertical joint.

The construction of the granite watertight faces was delayed until th concrete walls in their vicinity had been built to the full height and settl ment had taken place. Large recesses were left in the concrete walls fo this purpose, with numerous reinforcing rods projecting therefrom b which the concrete backing to the granite could be well bonded to th previously-constructed mass-work. Similar recesses were formed in th sills for the same purpose.

The linings for the main pumping and filling culverts were of flange cast-iron sections bolted together. The linings were comparatively ligh as they had to act mainly as shutters for the mass concrete surroundin

them; where the culverts joined the valve-frames they were of heavier section, designed to withstand the hydraulic pressure.

It is of particular interest to note that the Contractors were ordered to commence the work on the 1st June, 1931, and that the dock was opened by His late Majesty King George V on the 26th July, 1933, 26 months later.

Quantities.

Amongst the principal quantities dealt with were :—

715,000 cubic yards of open excavation;
580,000 cubic yards of trench and "dumpling" excavation;
460,000 cubic yards of concrete in walls, floor, etc.;
18,000 cubic feet of granite in sills, jambs, rubbing-courses, steps, etc.;
1,700 tons of cast iron in culvert-linings.

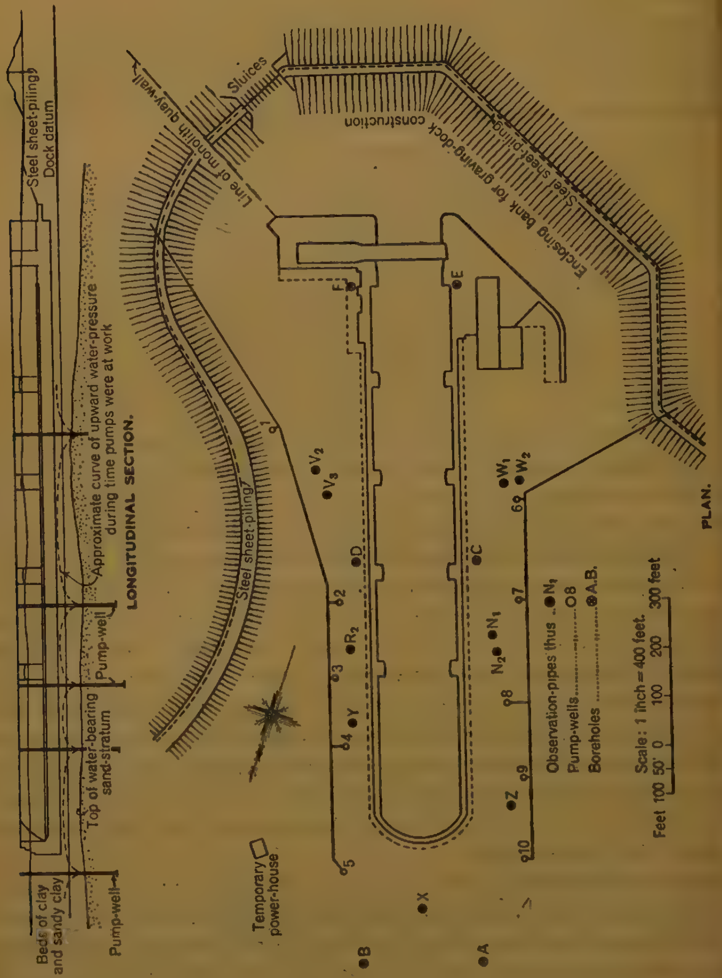
Artesian Water.

Six trial borings, lettered A to F on *Figs. 14* (p. 202), were put down to an average depth of —10·00 to explore the strata through which the trenches and floor excavations would have to be sunk. The order in which they were carried out was E, F, C, D, A and B, and whilst the first four disclosed the ordinary strata of the Bracklesham Beds as expected, at A and B a layer of sand containing water was encountered at a level of —3 feet, the water rising to a free level of 110·00. From this it was evident that the top of the water-bearing sand stratum sloped downwards towards the dock-entrance, and further bore-holes were put down along each side of the site to explore this slope. These indicated that for about two-thirds of the length, measured from the head, there was a risk that the water-pressure would burst through the overlying beds of clay when the excavations for the walls and floor were nearing their final depths; for the remaining one-third of the length the overlying beds of clay were of sufficient thickness to overcome the water-pressure.

From the information disclosed by the bore-holes and from samples of the sand in the water-bearing stratum, a system of ten wells for lowering the water-pressure was designed by Dr.-Ing. Willy Sichardt; the positions of the wells are shown in *Figs. 14*. At each well-site a 24-inch-diameter tube was sunk, and when this had penetrated a sufficient distance into the water-bearing stratum a 14-inch diameter pipe, the lower end of which for a length of about 30 feet was perforated and wrapped with a fine copper mesh to form a filter, was lowered to the bottom. The 5-inch annular space around the 14-inch pipe was then packed with clean fine gravel in the vicinity of the filter, and with puddled clay above it, the placing of the fine

gravel and puddled clay being done concurrently with the jacking out of the 24-inch-diameter tube. Thus, whilst the water could gain access to the 14-inch-diameter pipe, the sand was kept back by the gravel and copper-mesh filter. Each well was then equipped with an electrically-operated

Figs. 14.



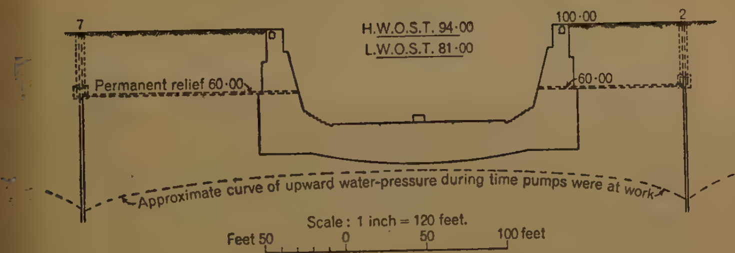
POSITION OF WELLS AND OBSERVATION-PIPES.

submersible pump, and was connected to discharge-mains which carried the pumped water outside the enclosing bank. In some of the wells more than one water-bearing stratum was encountered, separated by layers of impervious clay. In such cases a perforated filter-pipe was provided at each of the requisite levels.

For the operation of the pumps a supply of electricity was brought rom the Southampton Corporation's mains to the switchboard of a emporary power-house. As it was vitally necessary to keep the pumps oing continuously two diesel-engine generators (afterwards installed as art of the permanent plant at the pumping station) were provided o guard against the possibility of a breakdown in the main supply. Each f these engines was capable of generating sufficient current for all the well-umps, and could be started up at a moment's notice.

Ten 2-inch-diameter sounding-pipes were sunk to observe the effect n the water-lowering process when the pumps were in operation. These ipes were perforated and wrapped with wire gauze in a somewhat similar nanner to the pipes in the wells. *Fig. 15* shows the average free level of he water observed in the sounding wells during the pumping period.

Fig. 15.



Cross Section at Wells Nos. 2 and 7, showing Level of Permanent Relief of Artesian Water.

When the pumps were no longer required they were stopped one by one, the cessation of pumping operations being spread over a period of about 8 weeks; by this means a sudden rise in the water-level and consequent risk of cracking the fresh concrete was avoided (*Fig. 16*, p. 204).

Careful consideration was given to the question of whether or not the water under pressure in the sand would be likely to affect the dock in any way after its construction had been completed and the pumps had been removed from the wells. Evidence gained during the excavation had shown that the clay overlying the water-bearing stratum was not everywhere homogeneous, and that in a few places it was intersected by faults and sandy beds; although these were only local there were signs that the water could creep through where they occurred and impinge on the underside of the floor. The possibility then was that the pressure might accumulate to such an extent that the weight of the walls and floor might not have been sufficient to overcome it. In view of this, horizontal pipes at level 60·00 were connected to each of the tube-wells as they were in turn put out of action, the pipes being carried through the dock-wall, thus turning the wells into permanent relief-points.

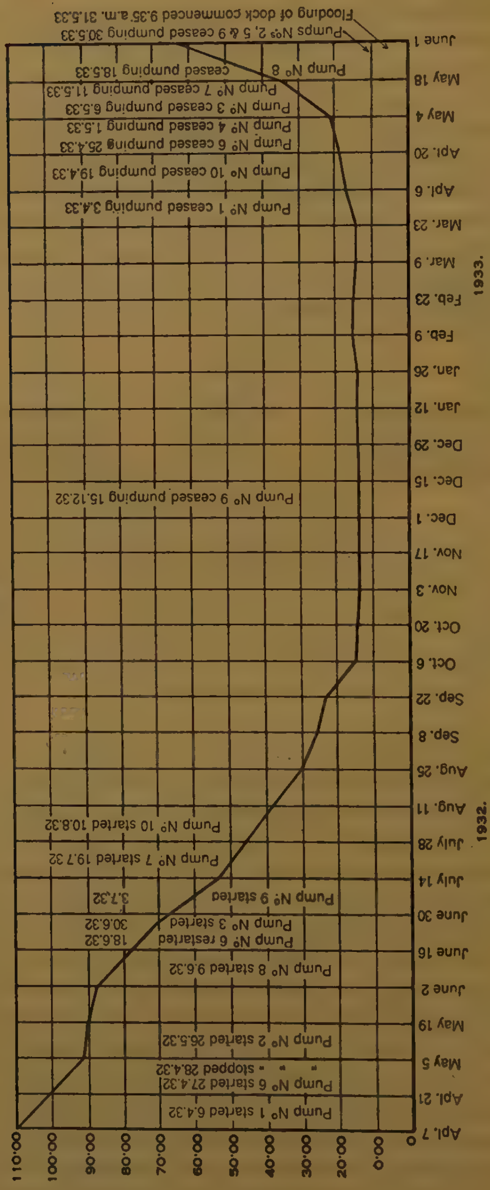


Fig. 16.

AVERAGE WATER-LEVEL FROM COMMENCEMENT TO FINISH OF PUMPING OPERATIONS.

Caisson.

The dock-entrance is closed by a double-faced steel sliding caisson, which is drawn back into a camber when ships are passing into or out of the dock. The caisson measures 139 feet 9 inches long on the centre-line and is 29 feet 6 inches wide over the timber meeting-faces. The caisson groove is provided with a watertight stop along each side, the inner stop being for use under ordinary circumstances when the dock is dry, and the outer stop when it is required to impound the water in the dock with a falling tide outside; the distance between the inner and outer stop is 30 feet, or 6 inches wider than the caisson over the timber meeting-faces. In addition, an emergency stop is provided at the extremities of the east and west wing-walls, against which the caisson is placed when it is necessary to pump out the whole length of the dock (that is, including the entrance and caisson-camber) for the purpose of examining and repairing the caisson slide-ways and rubbing-courses. The caisson is splayed at the ends to facilitate floating it out from the groove in which it normally operates to the emergency stop, where, when scuttled, it sits on granite rest-blocks sunk in the concrete apron.

The caisson was built and launched at the Haverton-Hill-on-Tees yard of the Furness Shipbuilding Company, Ltd. It was towed to Southampton and placed in Trafalgar graving dock (No. 6) for the finishing processes to be carried out prior to being towed into position at King George V graving dock.

The jambs and sills of the three stops are constructed of granite, and were dressed in position with patent axes in the usual manner and were finally rubbed down with carborundum; the rubbing-courses in the caisson-camber, which act as guides for the caisson, were also of granite, machine-polished at the quarry, and were set accurately to the line of the finished sill-faces, no subsequent dressing being done.

Eight flights of granite steps provide access to the floor of the dock, two being at the head, one on each side of the entrance, and one alongside each of the four timber-slides through the dock walls.

Greenheart Tests.

The timber used for the meeting-faces on the caisson was greenheart. As no information appeared to be available regarding the mechanical strength of this timber in structural sizes, it was considered desirable that tests should be made to ascertain the behaviour of the timber under heavy load, and to establish a working stress on which the design could be based.

Four pieces of uniform character and comparatively free from defects were selected for test and were prepared to the following dimensions: two 20 inches long by 10 inches by 10 inches, and two 20 inches long by

14 inches by 14 inches. The tests were carried out in a 500-ton hydrau machine at the Building Research Station, Garston, near Watford.

The results were as follows :—

Piece No.	Size.	Compression-stress at limit of proportionality of stress to strain:		Compression-stress at t maximum load:	
		lb. per square inch.	tons per square foot.	lb. per square inch.	tons pe square foo
1	10 inch by 10 inch	1,030	66	2,420	156
2	,, ,,	1,010	65	2,510	162
3	14 inch by 14 inch	1,440	93	2,300	148
4	,, ,,	880	57	1,960	126

The 10-inch by 10-inch pieces were practically free from defect, a were probably rather above the average in quality; they gave consiste results, both at the limit of proportionality and at the maximum load wh failure occurred. The 14-inch by 14-inch pieces, although comparativ sound, were slightly defective. They did not give such consistent resu as the 10-inch by 10-inch pieces, and the fact that the compressive stre at the limit of proportionality in the case of piece No. 3 was approximat 50 per cent. above the remainder was considered to be abnormal.

Having regard to the fact that the timber would be firmly fixed betwe steel angles on the caisson, and lateral expansion under load would thus restrained, and that longitudinal expansion would be resisted in timber long lengths, it was considered that figures in excess of those obtained the test could reasonably be expected under working conditions, and a sa working stress of 40 tons per square foot was adopted.

Culverts and Pumping-Station Equipment.

As previously stated, a site has been reserved on the west side of t present dock for another dock to be built in the future, and the pumpi plant has been designed so as to be capable of dealing with both. Th requirement resulted in the necessarily complicated system of culver shown in Fig. 17, Plate 1. In designing the lay-out of the culverts t following operations had to be provided for :—emptying, draining, fillin impounding, and pumping storm-water, with the possibility of three these operations being necessary at the same time when the second gravi dock is built.

Two filling-culverts, each 10 feet in diameter, are provided, one each side of the entrance. On the east side the culvert is led into the ba end of the caisson-camber, the water flowing through the camber to anoth culvert 10 feet in diameter situated near the open end, and thence into tw 6-foot 6-inch diameter culverts communicating with a pair of sumps on t

st side of the dock-floor. By this means a flow of water is induced along e length of the camber which helps to keep it clear from silt; furthermore, keeping valve No. 22 open, resistance to movement is lessened when e caisson is being drawn back into the camber. The filling culvert on e west side connects with the two 10-foot-diameter suction-inlets on the ock side of the suction-valves, the water entering the dock through a pair sumps similar to those on the east side. The water entering the dock om the sumps is deflected upwards at floor-level, so as not to impinge on e keel-blocks and thus tend to carry them away. The four sumps in the ock-floor are connected across the dock by 4-foot-diameter culverts, so at they also function as drainage-sumps when the dock is being pumped it.

The main pumping equipment consists of four centrifugal vertical-pindle double-inlet pumps, having 54-inch-diameter delivery- and 60-inch-iameter suction-branches; each pump is driven by a 1,250-b.h.p. syn-hronous induction motor operating on a 6,600-volt 3-phase 50-cycle apply. The dock, when full at H.W.O.S.T. and having no ship therein, olds 260,000 tons of water, and the main pumps are capable of dewatering in 4 hours.

For floor-drainage three centrifugal vertical-spindle single-inlet drainer-umps, having 16-inch delivery- and 18-inch suction-branches, each riven by a 200-b.h.p. motor, are provided.

For the supply of sea-water to the auxiliary condensers whilst certain hips are still afloat in the dock, a 10-inch centrifugal vertical-spindle ump, driven by a 35-b.h.p. motor, is provided. For the supply of ondensing water to the ship after the dock is pumped out, a 21-inch-iameter main is provided, from which a connexion can be made to the hip below the water-line; at certain conditions of high tide the water ows under gravity, but at low tide it is necessary to increase the flow by eans of a booster-pump. To meet this condition two 16-inch centrifugal ow-pressure vertical-spindle circulating-pumps (each as a stand-by to the ther), driven by 32-b.h.p. motors, are provided.

In case of fire aboard a ship when the dock is dry, two 8-inch two-stage entrifugal vertical-spindle pressure-pumps, driven by 135-b.h.p. motors, re provided. These pumps supply water at a pressure of 120 lb. per quare inch to a 10-inch-diameter fire-main from which a connexion is ade to the fire-fighting appliances on the ship. The 12-inch-diameter resh-water main along each side of the dock is available for a further upply in case of emergency.

For draining the pump-chamber, two 4-inch house-pumps are provided.

The pump-motors are placed at cope-level so as to obviate damage to hem should the pump-room be flooded as the result of an accident to the ump-casings or branch-pipes. All the pump-motors, with the exception f those on the main pumps already described, operate on a 415-volt -phase 50-cycle supply.

Auxiliary Electric Supply.

The current for the dock, as elsewhere for the dock estate, is suppl by the Southampton Corporation. Should this supply fail during a dock or an un-docking process it may be necessary quickly to close certain of t valves by power, and to meet this contingency two 125-kilovolt-amp alternators each driven by a four-cylinder vertical cold-starting die engine are provided, each being a stand-by to the other.

Pump-Valves.

A sluice-valve is provided on the suction- and delivery-branch of ea pump. Those on the main pumps, and also on the delivery-branch of t drainer-pumps, are electrically operated; the valves on the suctio branches of the drainer-pumps are hand operated.

Each pair of the main pumps connects with a common discharg culvert, and in the event of one of a pair stopping while the other continu to run, or of a failure of the current when the tide-level outside was high than the water in the dock, there was a risk that damage would be done a reversal of flow. To meet either of these contingencies, special apparat has been provided to enable the valves on the delivery side of the ma pumps to close under gravity in 15 seconds.

Culvert-Valves.

Valves Nos. 1 to 8, 12 and 13, and 19 to 22, on the suction-, discharg and impounding-culverts, are 10 feet in diameter. Nos. 9 to 11 are 6 fe 6 inches in diameter, and Nos. 14 to 18 are 3 feet in diameter. They are electrically operated by separate motors housed in watertight chambe sunk below ground-level.

Control-Gallery.

Practically all the pumping-station operations are controlled from gallery overlooking the whole of the motor-floor, and an illuminated diagra on the wall opposite the control-desk contains a plan of the dock-entran with all culverts, main pumps, drainer-pumps, pump-wells, and ma sluice-valves. Red and green signal-lamps at each valve-position on t diagram indicate whether the valve is open, half open, or closed.

Electricity Sub-Station.

The station is also an electricity sub-station, equipped with transforme and converters for dealing with bulk supply.

Keel-Blocks.

The keel-blocks are spaced at 2-foot 3-inch centres, and occupy a leng of 950 feet 10 inches. They are 16 inches wide and consist of five ste

astings, the top and bottom castings being of uniform depth throughout nd the remaining three tapered. A mild-steel tapered cotter in a slot hrough a lug on the thin end of the centre wedge-casting is provided to orrect any tendency for the latter to slip. The cast-steel blocks are surnounted by a 16-inch by 12-inch elm cap carrying a softwood pad. Three 1-inch diameter galvanized clench-bolts are provided to strengthen he elm caps against bursting pressure across the grain, and the elm caps re secured to the top castings by galvanized dog-bolts. Anchoring chains re fitted to fifty blocks at the forward end and to one hundred at the after nd of the dock.[1]

Keel-Block Tests.

Two of the keel-blocks were tested to destruction in an 8,000-ton press t the Sheffield works of Messrs. Firth and John Brown, Ltd. They were nounted on a greenheart pad and the pressure was applied to the top hrough the medium of two steel blocks, having a combined depth of 2 inches, the lower block being 24 inches long by 16 inches wide, with ounded corners. Dial-gauges recorded the compression in the steel castings nd the greenheart pad ; compression in the elm cap was measured direct.

The results of the tests were as follows :—

	No. 1 Block.	No. 2 Block.
Centre clench-bolts in the elm cap failed at	1,067 tons.	1,228 tons.
Cast-steel blocks failed at	1,873 ,,	2,034 ,,

In the first block the centre clench-bolt was placed below the centreine of the cap, and the elm was squeezed out to a considerable extent above the bolt ; this caused the washers on the centre bolt to be forced out on their upper edges and the washers on the outer bolts to be forced out on their inner edges, resulting eventually in the failure of the clenchbolts both by tension and bending under the heads.

In the second block the centre clench-bolt was placed above the centreine of the cap ; in this case the elm did not squeeze out above the washer plates, and was therefore effectively constrained with the bolts in tension only.

The cast steel failed by direct compression through the top block. The wedge casting slipped $\frac{3}{32}$ inch in the first block and $\frac{1}{4}$ inch in the second block ; the mild-steel cotters fixing the centre wedges were bent, but showed no signs of undue stress. The greenheart pad used in the first test stood up to the final load of 1,873 tons without any sign of distress, but that used n the second test split at the ends when the load had reached 1,389 tons.

Movable Bilge-Blocks.

The bases of the movable bilge-blocks consist of steel plates and

[1] The keel-blocks are illustrated in *Figs. 21*, p. 221.

angles built in the form of a box-girder, the table being 16 inches wid
They are surmounted by two 16-inch by 12-inch oak caps laid on the fl
secured to the bases by galvanized-steel straps and bolts.

Dock Cranes.

The dock is equipped with an electric travelling crane on each side.

The crane on the west side is of 50 tons capacity at a radius of 110 fe
the speed of the hoist being 10 feet per minute. A traverse hoist of 15 to
operates at 115 feet radius with a hoist-speed of 33 feet per minute. A
auxiliary hoist of 5 tons operates at 125 feet radius with a hoist-speed
100 feet per minute. The main hoist lowers under the control of
hydraulic brake, and the others are controlled by electric floating brak
The jib is of the luffing type with an average luffing speed of 6 feet p
minute. The sluing speed is one complete revolution in 4 minutes. T
gauge is 30 feet and the crane travels under power at 25 feet per minu
The crane rails are extended to the west wing-wall, so that heavy lifts c
be taken out of a barge and placed in the dock.

The crane on the east side is of 10 tons capacity at 60 feet radiu
the speed of the hoist being 50 feet per minute, with electric floating-bra
control for lowering. It is designed for level-luffing at 60 feet per minut
The sluing speed is 1½ revolution per minute. The gauge is 18 feet an
the crane travels under power at 50 feet per minute.

Caisson-Hauling Machinery.

The caisson-hauling machinery is electrically operated and is plac
at the western end of the caisson-camber. The main machinery an
motors are housed in a brick building, with the barrel pinion-shaft extend
through the walls at each side to the 7-foot diameter main driving barrels
the open. The winding barrels are driven by two main motors (duplicat
of each other), each capable of moving the caisson at the required maximu
speed. The main motors are coupled to the common pinion-shaft by d
clutches, so that if one motor fails it can be immediately disconnect
and the other brought into operation.

For the slow running of the caisson, the barrels are driven by tw
barring motors (again duplicates of each other), each capable of movi
the caisson at the required slow speed. The barring motors are connect
to the main gearing through double-reduction 10-to-1 gearing to gi
one-tenth of the full speed. Each barring motor is connected through i
gearing, and finally through a friction-drive, to the main armature spind
the friction drive being applied by a weight and released by a solenoid.

All motors being reversible, no reversing gear is provided. The sl
speed of travel is 2½ feet per minute and the maximum 25 feet per minu

The control of each set of motors is carried out by three push-butto
labelled "slow," "run," and "stop" respectively. When the "slow

utton is pressed, the barring motor is connected in circuit and gradually rought up to speed, moving the caisson at the rate of 2½ feet per minute. fter a travel of about 2 feet the "run" button is pressed and the main otor is brought into action; the solenoid of the barring motor is then nergized and releases the friction-drive, thus freeing the barring motor and anding over the drive to the main motor which gradually brings the speed f the caisson up to 25 feet per minute. At about 2 feet from the end of the ravel the main motor is disconnected by means of a limit-switch, and the rive handed over to the barring motor, the solenoid being de-energized; he falling weight, which is controlled by a dashpot, gradually applies the riction-drive, the barring motor finishing the drive at 2½ feet per minute, nd being finally stopped by another limit-switch operated by strikers at he end of the caisson. The controls for operating the various movements re placed at the front of the machinery-house, within easy control of one nan standing in such a position as to have a good view of the working area.

The two hauling-ropes are 6½-inch-circumference specially-flexible alvanized plough steel, with manilla core. One end of each is secured to he camber end of the caisson direct, and after passing under and around he winding barrel, the rope passes over the barrel and around a 5-foot-liameter horizontal sheave sunk slightly below ground-level, and thence o a fixing on the camber end of the caisson; thus the ropes run over the ops of the winding barrels for hauling the caisson out of the camber, and n the undersides of the barrels for hauling it into the camber. The slack f the ropes is supported by rollers carried on steel frames, fixed to the walls f the camber.

Condensing-Water Culverts and Storm-Water Drainage.

The former tidal mudlands extended up to the Southampton Corporation's electricity-station, as shown in *Fig. 3* (p. 187). Sea-water for condensing purposes was obtained from an adjoining cooling pond, which was replenished at high tide. As water access to the cooling pond would be cut off by the reclamation of the West bay, the Southampton Corporation required the Railway Company to provide culverts for the purpose of conveying from and to the estuary 4½ million gallons of water per hour. Two culverts each 7 feet in diameter were provided, one being for suction and the other for discharge, connected at the electricity-station to a suction-trough and a discharge-trough respectively.

The Corporation also required the Company to extend the storm-water drains that formerly discharged on to the foreshore of the bay, so that they should discharge outside the line of the new quay-wall. These drains were dealt with in two sections, the first commencing at Southampton Central station and running eastwards, the second commencing about 700 yards west of the Central station and running westwards. In both sections a new storm-water culvert was constructed to which the existing storm-water

drains were connected. The positions of the culverts are shown in Fig Plate 1.

The new storm-water culvert for the first, or eastern, section was ma 7 feet in diameter throughout its entire length. From its commencement Southampton Central station as far as the Corporation electricity-stati a distance of about 340 yards, it was built in trench with a level invert 86·50, and from thence was built (at a lower level) in the same trench the condensing-water culverts for a further length of about 1,020 yar where it diverges westwards so as to pass under the storm-water pump station at the eastern end of the new quay-wall, as will be described lat the condensing-water culverts continued southwards, the one for a leng of about 110 yards to an intake, and the other for a length of about 1 yards to an outlet. The intake and the outlet were built just outside t embankment enclosing part of the reclaimed area, and were placed as apart as practicable to prevent warm water from the outlet re-entering t system through the intake.

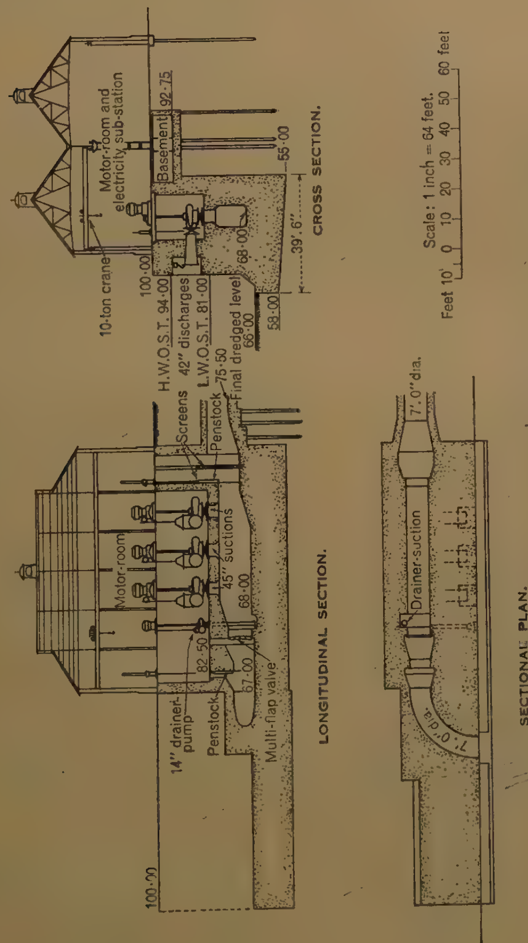
By an arrangement of penstocks at the Corporation electricity-stati the two condensing-water culverts can be made interchangeable supply or discharge, and, in addition, the storm-water culvert can temporarily used as an emergency discharge-culvert for condensing wa during the time that either of the condensing-water culverts is out of acti for inspection, cleaning, or repair. Pipe connexions to the three culve permit sea-water to be supplied to the Southampton Corporation bat and of the return of used water to the river. The baths can be fill by opening a valve connecting with the condensing-water discharge-culve as, owing to the hydraulic gradient between the discharge-trough at t electricity-station and the tide the free level of the water in the discharg culvert opposite the baths is always higher than the tide; conversely th can be emptied at low tide by opening a valve connecting with the co densing-water suction-culvert, as owing to the hydraulic gradient betwe the tide and the suction-trough at the electricity-station, the free lev of the water in the suction-culvert opposite the baths is always lower th the tide. If it is desired to empty the baths at any time other than th of low tide, this can be done by opening a valve connecting with the storm water culvert and pumping it out by means of the plant installed in t storm-water pumping station.

Storm-water Pumping Station.

Normally the flow in the storm-water culvert is gravitational, but order to guard against flooding in the streets and property in the vicinity the former foreshore and of the reclaimed land during a severe stor or high spring tide, or the coincidence of both, a storm-water pumpi station (shown in *Figs. 18*) has been provided. The sub-structure of t station forms the eastern end of the quay-wall, and was constructed insi a single-skin steel-pile box-dam sunk through the tipped gravel bank.

The storm-water flows through the culvert which passes under the station, a multi-flap valve being provided to prevent back-flow of the tide. A float-control chamber near the Central station, connected to the pumping station by a land-line, contains apparatus which automatically gives

Figs. 18.

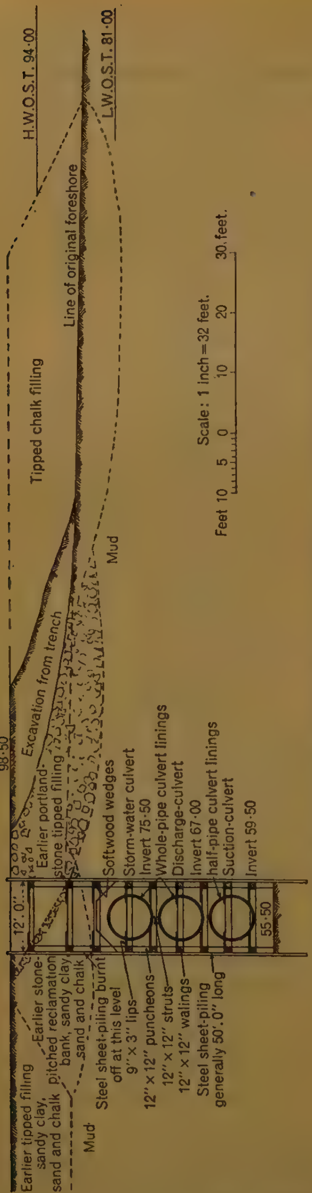


Storm-Water Pumping Station and Electricity Sub-Station.

warning in the station of impending flooding and of the necessity of bringing one or more of the storm-water pumps into action.

The pumping equipment consists of three vertical-spindle single-inlet pumps, with 42-inch delivery- and 45-inch suction-branches. Electrically-operated sluice-valves are provided on the delivery- and suction-side of each pump, and hand-wheels are also provided for use in emergency.

Fig. 19.



Cross Section of Trench and Culverts ("Vertical" System).

A 14-inch vertical-spindle sing
inlet drainer-pump and a 2-in
vertical-spindle single-inlet hou
pump are also provided.

The station is also an elect
sub-station, equipped with tran
formers and converters for deali
with bulk supply.

Culvert-Construction.

The culverts were formed wi
pre-cast reinforced-concrete lining
7 feet in diameter, 4 inches thi
and 6 feet long, surrounded by ma
concrete. Where the culverts we
built one above the other, as show
by *Fig. 19*, the lowest was form
by two semicircular linings, as
was considered unsafe to stri
enough of the lower trench-timbe
ing to permit the bottom culve
lining to be placed as a comple
circle.

From A to B (Fig. 1, Plate
the trench had to be sunk throu
an old bank of large rubble ston
about 10 to 20 feet deep.

As originally designed the thr
culverts were placed one above th
other, as shown in *Fig. 19*, and we
so constructed between the points
and D (Fig. 1, Plate 1). The trenc
was about 43 feet deep. It wa
lined with steel sheet-piling, and wa
timbered with nine settings of 1
inch by 12-inch timber walings a
struts, the latter being placed 1
feet apart horizontally, and a sing
strut being used at the junction
the walings. Softwood wedges we
used, and the struts were lippe
and the walings puncheoned-up in the usual manner.

Prior to driving the steel sheet-piling the rubble stone was excavate
in a runnered trench, the two or three top settings of timbering bein
placed. The runners were then withdrawn one by one, the steel pil

substituted and driven to full depth by means of an automatic steam hammer. During the withdrawal of the runners a certain amount of stone, gravel and soil caved into the trench in certain places, and the cavities had to be made good after the piling had been driven.

Below the rubble stone the ground consisted of soft clays and peat, until a stratum of gravel was reached near the foundation-level; under the gravel was a deep bed of firm greensand. The water-content of these materials varied, but generally speaking they were fairly dry in the undisturbed state. An appreciable quantity of water percolated through the interlocks of the steel sheet-piling from the rubble-stone bank, which was open to the tide, and as it fell into the trench it tended to soften the clays and greensand.

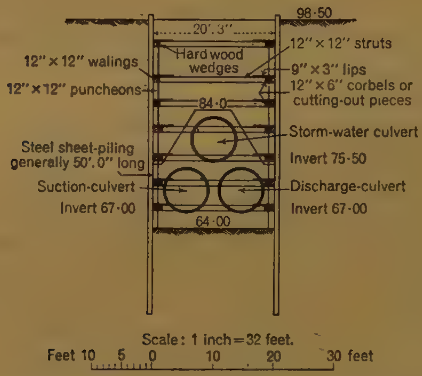
During the excavation of the trench it was noted that the pressure on the sides was very heavy, and in consequence of this, and of the soft nature of the material in the core of the trench, increased perhaps by the action of the water which percolated into the trench from the rubble-stone bank, considerable bulging of the sides took place, the steel piles bending inwards, and the greater portion of the trench, particularly at the bottom, being less than the intended 12 feet in width. This appeared to occur mainly before the material could be excavated and the timbering inserted. The extent of the bulging varied, and in the narrowed part the trench was just wide enough to permit the culverts to be constructed, a better-quality concrete being placed around the lowest culvert in places when the width was less than that shown upon the contract section.

It was further noted that the trench had moved over at the top seawards, and this movement eventually reached a maximum of 4 inches. This seaward movement, or leaning over, of the trench was considered to be largely due to the fact that a few feet seawards of the trench the ground sloped away from the side of it down on to the mud foreshore, about 12 feet lower than the ground on the landward side. It was therefore decided to form a bank around the foreshore, about 100 feet wide, to provide support on the seaward side of the trench and to stabilize the ground generally; this was done by tipping out chalk from railway wagons.

In view of these experiences and of the fact that some adjoining property was beginning to show signs of damage, it was decided to amend the design and to build the culverts in approximately "shamrock" shape, as shown in *Fig. 20*, using a heavier section of steel sheet-piling for lining the trench and driving it well below the bottom of the trench. As a further precaution the timbering was strengthened-up by placing the frames closer together vertically, and in the lower four frames by using double struts at the junctions of the walings, with 12-inch by 6-inch cutting-out pieces at one end, and sometimes at both ends, of the struts. Hardwood wedges were used, the struts were lipped and the frames laced where necessary. Generally, the upper portion of the steel sheet-piling above the concrete

was withdrawn, the lower part being left in, even where, as was the case some parts of the work, timber foundation-piles had been driven. In t manner the work was satisfactorily completed. It meant, however, th the suction-culvert is permanently lower between the points C and D th elsewhere, and a special sump was provided at D for pumping out t portion when the suction-culvert has to be dried out for inspection.

Fig. 20.



Cross Section of Trench and Culverts ("Shamrock" System).

Second Section of Storm-water Drainage.

The second section of the storm-water drainage discharges und gravity at the west end of the quay-wall, but in cases of high tide or hea storm the discharge can be dealt with at the King George V gravi dock pumping-station, wherein warning is automatically given of impen ing flooding by apparatus provided in a float-control chamber ne Millbrook station.

Subsidiary Works.

Passenger and Cargo Sheds.

Eight brick-built single-storey passenger and cargo sheds, shown in cro section in *Figs. 7* and *8* (p. 194), have been provided in four pairs lengt wise. They have a combined length of 5,890 feet, and a uniform width 150 feet. Each pair is separated by a centrally-placed buffet and loun for the use of passengers, with entrance doors from each of the adjoini sheds.

One railway line is provided inside the front of the sheds and o inside the back; on the latter all the passenger trains and most of the goo trains are dealt with. The shed-floors slope up from the level of the fro line to 3 feet 3 inches above the back, so as to facilitate the entraining an

etraining of passengers, and the handling of cargo to and from rail. The oors along the front occupy 50 per cent. of the length. A balcony for he use of the public is provided along the greater part of the front of ach shed.

Carriage-Cleaning and Warming Shed.

A brick-built carriage-cleaning and warming shed 760 feet long by 8 feet wide has been provided. It has six lines of railway track, each apable of accommodating one twelve-coach special train. Here the rains are warmed by steam before they are shunted into the sheds for assenger use, and the building is further equipped with the means for eplenishing the train water-tanks, and for supplying gas to the kitchen-ars for cooking purposes.

Railway Sidings.

Two lines of sidings have been provided along the entire length of the new quay; these connect with three lines behind the passenger and cargo sheds, and all connect with groups of sidings further landwards arranged as "reception inwards," "marshalling inwards," "marshalling outwards," and "departure" sidings. At present only the nucleus of these groups has been provided, with space to add to them as and when necessary. Altogether 26 miles of 90-lb.-per-yard chaired track have been laid on the new estate.

Vehicular Roads.

The easternmost length of 400 yards of Herbert Walker Avenue was made with hand-packed limestone foundation, hoggin, and rolled tar-macadam. Except for this all the vehicular roads were made of concrete. They were laid for the full width in alternate lengths of 20 feet, the primary lengths being formed with transverse screeds and acting as screeds for the secondary lengths after setting. Plain butt-joints were adopted transversely, each joint resting centrally on a concrete pad 24 inches wide by 7 inches deep, extending across the full width of the road. A strip of bituminous felt was secured across the face of each of the transverse joints after the primary lengths had set, to form expansion-joints.

As expected, the roads have sunk in places owing to the settlement of the reclaimed land; in such places the surface has been brought up to level where necessary with tar-macadam.

Conclusion.

The works were designed and carried out under the direction of Mr. F. E. Wentworth-Sheilds, O.B.E., M. Inst. C.E., then Docks Engineer, Southern Railway, under whom the Author served as Chief Assistant.

Messrs. Coode, Wilson, Mitchell and Vaughan-Lee, MM. Inst. C. were consulted when difficulty arose in sinking the quay-wall monolit and in the construction of the storm-water and condensing-water culver in connexion with the latter Messrs. Mott, Hay and Anders MM. Inst. C.E., were also consulted.

Mr. H. Wauchope, the Company's Docks Electrical Engineer, w responsible for the installation of the electrical equipment, mains a services.

The principal works and some of the subsidiary works were carri out under contract; the railway sidings, vehicular roads, drains, wat and gas-mains, etc., were carried out under direct administration the Docks Engineer's Department.

A special staff was formed for the design and execution of the work particular mention should be made of:—Mr. E. W. Beare, B.Sc. (Eng M. Inst. C.E. (Senior Assistant and in charge of design staff); Mr. G. E. Callow, B.Sc., M. Inst. C.E. (in charge of the construction of the quay-w and the passenger and cargo sheds); Mr. Frank Whyte, M.C., B.S M. Inst. C.E. (in charge of the construction of King George V gravi dock); Mr. V. R. Husband, B.Sc. (Eng.), Assoc. M. Inst. C.E. (in charge dredging and reclamation); Mr. Cecil Peel, B.Sc. (Eng.), Assoc. M. Inst. C. (in charge of the construction of the storm-water and condensing-wat culverts); Mr. D. J. MacG. Williamson, Assoc. M. Inst. C.E. (in charge the western section of storm-water culverts); Mr. W. J. Sincla Assoc. M. Inst. C.E. (in charge of work carried out under the Railw Company's direct administration).

The Contractors for the principal works, and their representativ on the site, were:—

Dredging and reclamation.	The James Dredging, Towage Transport Company, Ltd. (M G. H. James and Mr. G. H. Pursey).
Quay-wall, and passenger and cargo sheds.	Sir Robert McAlpine & Son (London), Ltd. (Mr. T. G. McAlpine and Mr. Donald Ma kenzie).
King George V graving dock and western section of storm-water culverts.	Messrs. John Mowlem & Compan and Edmund Nuttall, Sons Company (Joint), Ltd. (Mr. E. M Fitt, B.Sc., M. Inst. C.E.).
Caisson at King George V graving dock.	The Furness Shipbuilding Com pany, Ltd. (Mr. J. H. Cross).
Artesian-water wells at King George V graving dock.	Messrs. Siemens-Schuckert (Grea Britain), Ltd. (Mr. Helmu Wehe).

torm-water and condensing-water culverts.	Messrs. Charles Brand & Sons, Ltd. (Mr. J. M. M. Howat, Assoc. M. Inst. C.E.).

The Paper is accompanied by eighteen sheets of drawings, from some f which Plate 1 and the Figures in the text have been prepared, and by five hotographs.

Discussion.

The Author showed a number of lantern-slides illustrating the wor described in the Paper. In doing so, he mentioned that very heavi reinforced concrete was formed in and above the monolith-shoes to height 10 feet above the top of the shoes. It would be appreciated th it was impossible to calculate the amount of reinforcement, which had be put in more by judgement than by calculation. The monoliths ha to be designed in such a way that the shoe, if it struck an obstruction the middle, could act as a double cantilever, or, if it were held up at t corners, could act as a beam, and therefore the reinforcement was carri through on both the tension- and the compression-flange.

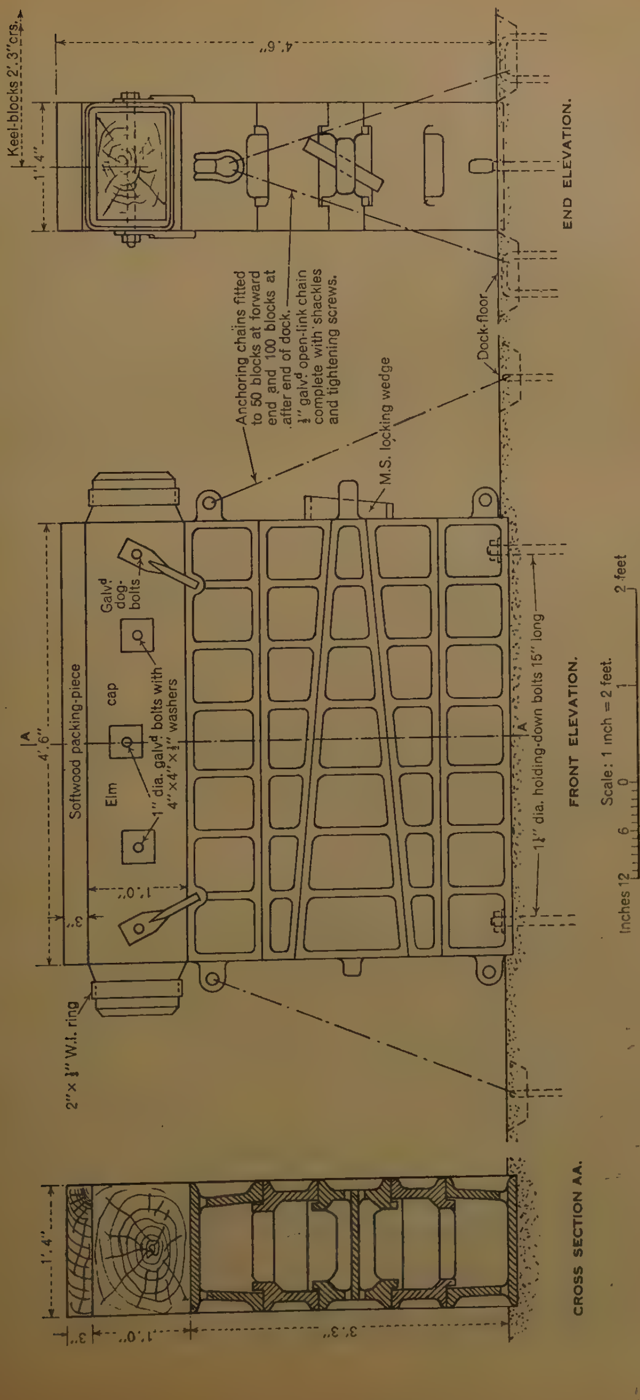
The final dredging depth alongside the quay was 45 feet, with an ou fall width of 150 feet. Beyond that the dredging depth was only 35 fee the reason being that the ruling depth of the channel from the sea to th docks was 35 feet at L.W.S.T.; since, however, ships such as the *Majest* and the *Leviathan* (which was then afloat) drew 40 feet of water, it w necessary to provide them with a berth at which they could lie afloat all states of the tide.

The front of the gravel embankment was dredged away after th monoliths had been sunk, but before the cope-work had been put on. was realised that the monoliths would pitch forward slightly when th support of the gravel was taken away from them, and they had done to the extent of about 2 inches. The cope-work was put on afterward so that it should not be cracked by the pitching of the monoliths.

The concrete roads were of some interest because, although they ha been placed on newly-reclaimed land, they had been remarkably successfu They consisted of a 7-inch slab with very light reinforcement top an bottom; there were no dowels in the joints, but underneath the joint wa placed a 2-foot by 7-inch sleeper-pad running the whole width of the roa Although the roads were only formed in 20-foot lengths, it had to b remembered that the traffic in Southampton docks was restricted to speed of 15 miles per hour, so that a form of construction used ther might not be satisfactory on main roads where high speeds were possible

With regard to the construction of the graving dock, the special jett built for sending the soft mud (which was useless as reclamation-materia to sea was very high, so that barges could be put under the mud-shoot any state of the tide. The mud was brought from the dock-enclosu by standard-gauge tipping wagons holding 11 cubic yards, and was di charged down the shoot into the hopper-barges. The design of the kee blocks used in the King George V graving dock was shown by *Figs. 2* which amplified the description of the blocks given on pp. 208–9.

Figs. 21.



KEEL-BLOCKS.

Mr. G. S. Szlumper remarked that he would not enter into any arg[uments] on the technical details of the undertaking, but he would like [to] mention the meticulous care which the staff had taken in the wo[rk]. Incidentally, he might mention that some 407 acres of land had be[en] added to England, which was no mean feat.

One thing which had particularly impressed him from the econom[ic] aspect had been the cost of the sluices that had been necessary [to] prevent erosion at the entrance to the enclosed areas. During sinki[ng] the monoliths had leant at various angles, but that had been very large[ly] rectified before they had reached their final position, and any slig[ht] irregularities had been rendered invisible by the concrete cope-wo[rk]. The difficulties in sinking had been very largely due to the presence [of] large boulders, which Mr. F. E. Wentworth-Sheilds and the Author h[ad] also had to deal with when they had been dredging for the floating doc[k]. Incidentally, the modification of the design from the deeper type [of] monoliths to the shallower type with a compensating platform at the ba[ck] had an economic advantage by providing a wall which was cheaper [per] foot run than would have been provided by the deeper type, and w[as] also quicker to construct. The shed-roof design had not received mu[ch] attention in the Paper. Resting as it did on the centre supports and n[ot] in any way upon the walls, it was well worthy of notice. The design w[as] not altogether original, but it was an advance on anything which exist[ed] at the time, and it had proved itself to be of sufficient value to be sim[ilarly] copied elsewhere.

The Paper seemed to him to be rather a cold-blooded account of wh[at] was to a large extent an epic work. Those who knew Southampton as [it] used to be and who were able to see it as it was at present, and who cou[ld] visualize what it might be in no distant future as a result of the wor[ks] described, would feel that a very great debt of gratitude was owing [to] the Author and to Mr. Wentworth-Sheilds, his predecessor, as well as [to] the other engineers and to the contractors.

Mr. F. E. Wentworth-Sheilds said that at the time that the wo[rk] described in the Paper was being carried out the Southern Railway ha[d] encouraged visitors to see the work. It had not been possible to have [an] unlimited number, but they had had as many as they could, and after t[he] work was completed there had been many trainloads of visitors.

He thought that there were four things with which the visitors ha[d] been particularly impressed. One was the scale and the style of t[he] passenger-accommodation, which was certainly very much better tha[n] anything which had hitherto been provided at Southampton. He wou[ld] not say that it was very much better than anything else which had bee[n] done in Great Britain, but certainly it might claim to be so having rega[rd] to the scale of the work, and the lay-out of the passenger-accommodatio[n] was well worthy of the premier passenger port of the country.

The visitors had also been impressed by the very fine piece of reclam[ation]

on-work which had been carried out. The quay-wall, which was to ccommodate eight large vessels, was 1½ mile in length, and behind that ı area of over 400 acres had been reclaimed, which was not merely ıfficient to accommodate the cranes, sheds and sidings used in connexion ith the quay, but also gave space for what might be called new industries, hich, for a railway port, was quite a new departure. It would be alized that, Southampton being a railway port, the exports and imports ere ordinarily taken from and to destinations which were a long way way from the port, but the Southern Railway had very wisely decided ıat it would be an attraction to have a number of industries which could ıake use not only of the deep-water quay but also of the excellent rail nd road access, and he was glad to say that advantage was being taken f the fine accommodation which had been provided.

Another thing which greatly interested those who saw it was the construction of the quay-wall. At Southampton they had tried at least a ozen different methods of wall-construction, because, as was well known, was a notorious port for quay-wall difficulties. The foundations were ot good, the clay being of a very slippery nature, and troubles abounded. n the present occasion, largely on the advice of the late Sir Frederick almer, Past-President Inst. C.E., they had adopted monoliths. Undoubtedly the work had been a success, but he was not at all sure that it onstituted the last word, and he would like to add that they had been ery much handicapped by the want of a rational theory of earthressures. He would like to take the opportunity of drawing attention the fine work in that respect which was being done by Dr. R. E. tradling at the Building Research Station. He believed that Dr. Stradng was going to produce a rational theory of earth-pressures, and he only ished that it had been available at the time the work in question had een in progress. He was convinced that it was well worth the while of very port-undertaking in Great Britain to do everything possible to ncourage that piece of research, which would result in the near future in mmense economies. At present, in order to play for safety, it was ecessary to carry out a great deal of work with big quay-walls which ere not really economical.

Finally, he thought that everyone was very impressed with something which Mr. Szlumper had referred; namely, that the work was a very ne piece of team-work. The Author had mentioned half a dozen ontractors who had carried out the principal work, but in fact the total umber of contractors engaged was more like two dozen, and they had ll co-operated to produce a fine result.

Sir Henry Japp observed that, although he had been connected only ith the dry dock, he hoped he would be excused if he said a few words bout the monolith quay-wall and the docks themselves. It would appear rom the experience gained with large liners that Scheme No. 2, with five etties projecting in a north-to-south direction parallel with the centre

line of the dry dock, might have been a better plan for dealing with shi- ping. He had heard from seafaring men that it was hardly possible take a big ship such as the *Queen Mary* away from the quay-wall with very strong south-westerly gale blowing. Perhaps when additio accommodation became necessary, parallel jetties might be substitut for the second pier shown in Fig. 1, Plate 1.

With regard to the monoliths, the difficulty seemed to be to get th to sink through the firm greensand, and instead of going down to a le of +6 they had bottomed at +29. When the firm with which he w connected had put in a tender for those monoliths, they had made p vision for pipes going down from the top of the monolith to the cutti edge to discharge high-pressure water-jets, so that the firm greensa might be broken up and swept into the middle of the wells, where it could grabbed, in order to allow the cutting edge to get down to the desired dep The reason that he had made that provision was because of experience whi he had had in sinking monoliths for the late Sir John Wolfe Barry, Pa President Inst. C.E., at the entrance to the Greenland dock at Roth hithe. There they had grabbed the monoliths out through ballast and t Woolwich and Reading beds until they rested on the Thanet sand. T Thanet sand was generally supposed to be very quick, but in that ca they had excavated 12 feet below the cutting edge, and in spite of all t kentledge they had piled on top the monoliths would not budge. Div had been sent down to disturb the wall of sand, but it was no use. had then asked Sir John Wolfe Barry to allow them to pump out t monoliths so that the Thanet sand might be forced in and become quic After a long discussion, Sir John allowed them to try one, and th pumped it out. No sooner was the water down than the sides caved and the cutting edge went down to its full depth. The following mornin they had all been very astonished to see a large hole in the foresho opposite the monolith and outside the cofferdam. All the monoliths we sunk in the same way, and on each occasion a big hole had formed in t foreshore, which had been filled up with clay. What had happen was that the Thanet sand which extended under the Woolwich a Reading beds right away from the channel of the river was forced the water into the wells of the monoliths, but it was so dense that soon as it stopped flowing it filled all the cavities, and no further flow w experienced.

The contract for the graving dock at Southampton was the one which he was specially interested, and he thought that Mr. Wentwort Sheilds had done a very fine thing when he had adopted the form contract for civil engineering works recommended by the Associati of Consulting Engineers. It was a very simple contract that was easi understood, as was the schedule of quantities which went with Mr. Wentworth-Sheilds had also showed great courage in using the wate lowering system that had been introduced by the Siemens Company. H

hat means he had avoided having a wet bottom for the excavation, and no blows had occurred. After the work was finished, Mr. Wentworth-Sheilds had allowed the wells to vent through pipes in the sides of the dock at the level of +60, and had thus prevented any chance of the invert being disturbed in the future by upward pressure. A rather interesting point was that when the water came through those relief pipes and ran down the side of the dock it stained the wall on a vertical strip down to the invert, and then when the dock was full of sea-water, the water from the wells, being fresh and being warmer than the sea-water, rose vertically and made a vertical strip of stain up to high-water level.

The concrete for constructing the dock was made with the excavated ballast, which was washed. It was obtainable in great quantities, and it was possible, owing to the thickness of the invert and to the massive walls —the invert being 25 feet thick and the voussoirs each having a volume of 1,000 cubic yards—on one or two occasions to reach an output of 12,000 cubic yards of concrete per week. There was an item in the schedule for the supply of imported sand to make up any deficiency, and quite a large quantity of that was used; he thought, however, that the Author had been under the impression that the price was a little high, as he did not use as much as might have been expected. The consequence was that the concrete now and again was what some people called "bony"; it was what he himself would call "Cassius concrete," because it had "a lean and hungry look." That did not matter, because the stability of the work depended on its weight, so that the dock was perfectly safe in spite of that little criticism. The cement used throughout the work was "Ferrocrete," used at 6 to 1, which gave the concrete a somewhat higher tensile strength than was usual in mass walls; in consequence, instead of having small shrinkage cracks about 300 feet apart, there was only one crack about 2 inches wide in the whole length of 1,200 feet.

Mr. R. F. Hindmarsh remarked that the quay and dry dock had been designed in such a solid and substantial way that they were likely to last and to add a very important part for many years to the great facilities offered by Southampton as a port. The works had been designed and carried out, and had been described in the Paper, in such a way as to leave little, if any, room for criticism, but there were a few points on which some amplification by the Author would be advantageous.

With regard to the reinforced-concrete bases formed in and above the steel shoes, perhaps the Author could add a diagram showing the reinforcement and how it was arranged and secured. With regard to the cleaning out of the wells, he did not gather from the Paper whether that had been done by divers, or whether any attempt had been made to pump out the wells for the purpose, and if so with what result. The Author stated that several of the monoliths had been found "to be damaged to a lesser or greater extent as the result of sinking difficulties,"

and it would be of interest to have some particulars of the damage an to know whether the Author thought that if the steel shoes had been greater strength and stiffness the damage might have been avoided. Th steel shoe was like a pile-shoe or the edge of a knife, and if anything wer wrong with either there was great difficulty in cutting into the materia He had recently been interested in the design of monolith shoes, but h monolith shoes were very much heavier and therefore more costly tha those described by the Author.

Mr. T. F. Allen said that the design-staff of the Civil Engineer-in Chief's Department of the Admiralty had been very interested in South ampton from several aspects, one of which was that of the cargo and trans sheds. When they had designed the Singapore Naval Base they had ha to allocate an area for handling naval stores, and they had decided tha the proper thing to do would be to take the best commercial practice a their guide. The methods used at Southampton had been studied an they had adopted the transit-shed principle, although not with the typ of roof used at Southampton. Their sheds were 500 feet long and 225 fe wide, and had a cross fall of 2 feet, giving a gradient of rather less tha 1 in 100.

He had been very interested to see the tests on the greenheart, whic he regarded as very valuable. There was one little point which he wou mention in that connexion; namely, that the Director of the Fore Products Research Laboratory at Princes Risborough had publishe certain figures of tests on greenheart, and had given the compressio stress at the limit of the proportionality of stress to strain perpendicul to the grain as 1,980 lb. per square inch. That was roughly double th figures of the test at Southampton, and was probably explained by th scale of the tests or the moisture-content of the various samples. Arisin from that, there was one small warning which occurred to him. In th tests of the Forest Products Research Laboratory the figure for the te parallel to the grain was given as 8,500 lb. per square inch, a ratio about 2 to 9 to the figure for a test perpendicular to the grain. Or authority, however, gave the compressive stress at maximum load c greenheart end grain as 700 tons per square foot (11,000 lb. per squa inch), and the ratio of side grain to end grain strength in hard wood roughly 1 to 2. Using information of that kind might have serio results, and therefore the Author's tests were extremely useful.

With regard to the monoliths, he would suggest that there were certa points which the Author might amplify. Two Papers on the Low Zambezi Bridge[1] had been presented to The Institution last year whic gave certain rates of sinking and values of sinking-effort. If some simil figures could be given for the Southampton monoliths they would be ver

[1] F. W. A. Handman, "The Lower Zambezi Bridge"; and G. E. Howort "The Construction of the Lower Zambezi Bridge". Journal Inst. C.E., vol. 4 (193 37), pp. 325 and 369. (January 1937.)

useful. Was any limit laid down for the minimum permissible distance horizontally and vertically between the shoes of adjacent monoliths? It seemed to him that there might be some risk in letting the cutting edge of one monolith get too near to the bottom of an adjacent monolith. He was also very interested in the appliances used for breaking down the supporting walls of sand under the cutting edges; they had apparently been very efficient.

In conclusion, would it be possible for the Author to give some figures of costs? In particular, he would like to know the dredging costs.

Dr. Brysson Cunningham remarked that the Paper dealt with the largest and, indeed, the only major British port-extension scheme, excluding re-modelling operations, of recent years. Considered as a record, however, in spite of the general excellence of treatment and the wide scope of the subject, there were one or two omissions of a rather important character in the Paper to which he would draw attention.

The operations had extended over a period of 10 years down to the present time, but there was an entire absence of dates with the exception of two on p. 201, relating to the graving dock. There was no indication of when the scheme of improvement was embarked upon and when the work was begun, nor, apart from the exceptions to which he had referred, when the component parts were completed. The second omission was, he considered, even more important. Quantities were given, but there was no statement of costs. The policy of withholding information on that aspect of constructional work—and he had noticed it in more than one Paper of late—was greatly to be regretted, and he trusted that the Author would be able to give, at least in general terms, some idea of the expenditure incurred in connexion with the more outstanding items. The financial side of engineering undertakings was no less important than the constructional side, and, regarding a Paper as a contribution to engineering knowledge, it was in his view a mistake, or at least a defect, not to disclose figures of actual outlay. The omission gave rise in the first place to the impression—perhaps quite erroneous—that the cost had been excessive, and even unjustifiable; he was not for a moment suggesting that that was so in the present case, but the criticism had been made about other Papers and it was as well to bear it in mind. In the second place, the engineering profession was deprived of some extremely useful estimating data.

He would also like to refer to the prevalent practice, admirable from a number of points of view, of British engineers of constructing their works so substantially that they appeared to be destined for centuries of service and to be intended to survive everything except earthquakes and modern air-raids. The quay-wall of the Southampton dock extensions was an example; the solidity and obvious stability of the work made it a suitable companion to the quay-wall of the Ocean dock built some 30 years before. In view, however, of the types of constructional work adopted

at ports on the Continent, where the physical conditions were not fund mentally dissimilar from those at Southampton, and also in view certain port-works on the other side of the Atlantic, it might be doubte whether the trouble and expense of such solid construction was qui justified, and whether, having regard to the changes so rapidly takin place in methods of transport, it was wise to build so substantially for s uncertain a future. That point had a rather peculiar significance fo Southampton, which was essentially a passenger port, being in fact th premier passenger port in Great Britain. Its goods traffic, althoug developing satisfactorily, occupied quite a secondary place; indeed, the absence of any great manufacturing hinterland, it was difficult to se how Southampton could attain any high standing as a port for goods. revolutionary trend in the means of passenger transport would serious affect the prospects of the port, and it was clear that some form of aeri transport was likely to become, in the not far distant future, a seriou competitor with the slower-moving ship.

He would like to ask the Author one or two questions on specifi points. Had the reduction in the volume of water entering the tid compartment due to the foreshore reclamation had any detrimental effe on the approach channel through the reduction of scour on the ebb-tide Had there been any excessive accumulation of mud in the deep bert alongside the quay-wall, and was any appreciable amount of dredgi required to keep them in serviceable condition? Had any settlement disturbance in the quay-monoliths been noticed since the work w completed?

He had had several opportunities, through the courtesy of M Wentworth-Sheilds and of the Author, of inspecting the work while was in progress, and he was indebted to them for much useful explanato information. Certain features which he had particularly noticed mig be mentioned. In the first place, there was the great improvement in th accommodation provided for passengers and in their comfort in th lounges, as compared with that existing at the Ocean dock. Then the was the efficiency with which the roads had been constructed over ma ground in spite of local settlement, and finally there was the refreshi novelty of the flower-beds and trim stretches of green turf at the entran to the dock-area and at the approach to the new quay. That last featur so uncommon in dock-areas, could not fail to make a favourable impressi on visitors to British shores, and was an example which might well followed elsewhere.

Mr. N. G. Gedye remarked that on several occasions during the co struction of the works described he had had the pleasure of examini them in some detail under the guidance of Mr. Wentworth-Sheilds, th Author, and others, and he had been particularly struck by the efficie working of the two appliances employed for excavating the wells of th monoliths; they seemed to be extraordinarily effective, and to ha

overcome the very serious difficulties which had been met with in sinking through the harder beds. Could the Author give some indication of the volume of water discharged into the dock through the permanent relief-pipes referred to on p. 203?

The difficulties that were encountered in carrying out one of the subsidiary works which had not been mentioned in the course of the discussion (namely, the culverts and intake pipes which were laid across the reclaimed foreshore) were considerable. He had several times examined those deep trench-excavations, and he had given some advice in connexion therewith to the contractors who were carrying out the works. The pressure exerted by the semi-fluid material of the foreshore was great, and the whole trench, as the Author recorded, moved in places towards the channel. That was one of the minor but important difficulties overcome by the engineers and the contractors in the course of carrying out the works.

He would also like to mention the very successful application of tube-well dewatering on the site of the graving dock. The German system had been applied and it seemed to have been extraordinarily effective. About the same time that that work was being done, he had had occasion to see a series of pumped wells employed in dealing with artesian water under somewhat similar conditions in the construction of the new Albert canal which was being built in Belgium between Antwerp and Liège. There the cutting was carried through high land, consisting of soil of a very treacherous nature, which lay above a subsoil near the bottom of the cutting which was under an artesian pressure approximately equal to the pressure at Southampton. The contractors in Belgium had been able by means of those artesian wells to keep the whole of the cutting dry during the construction, and to lay a permanent system of drainage-pipes throughout the cutting beneath the canal-bottom in order to discharge the water into the lower reach at the end of the cutting. Without having recourse to some system of drainage of that kind, the difficulties of construction of the dry dock at Southampton and of the canal to which he had referred in Belgium would, he was sure, have been enormously increased.

Mr. Athol L. Anderson, referring to Dr. Brysson Cunningham's remarks suggesting that the strength of the dock and the quay-wall might be excessive for commercial requirements, observed that as far as the Admiralty were concerned he was only too glad to see the conservative way in which the dock had been designed, because in addition to its being an immense commercial asset it might be called upon in an emergency to take a very large capital ship. With large and heavy capital ships the pressures on the keel-blocks under certain portions of the ship were very much larger than anything met with in commercial practice, and therefore he was glad to see that there was probably a factor of safety beyond what was perhaps necessary for commercial work, which would be available if the dock were required for use by capital ships.

There was one point about the dock which had caused him some little surprise. At the Admiralty they had always looked on commercial work as being in advance of their own, as they were very conservative, and could not afford to take up new methods until they had been thoroughly tested. They had, however, definitely abandoned the use of timber-slides for a good many years past, finding that they were a nuisance. The openings alongside the dock had to be covered over, whilst the covers themselves had to be of a light nature so that they could be lifted off; they were therefore usually made of timber, which wore out in course of time. Further, the covers were often situated where it was desired to lay a railway-siding. All equipment was therefore lowered or lifted by a crane on the dock-wall in naval dockyards. In view of that fact he would be interested to know why timber-slides were still used in commercial practice.

Mr. C. P. Taylor, referring to the two cross sections of the quay (*Figs.* 7 and 8, p. 194), said that the difference in depth was considerable, whilst the only alteration in design occasioned by that difference appeared to be the concrete slab at the top over the triangular void behind the monoliths. He could not help feeling that the cost of that slab was bound to have been negligible compared with the cost of the extra sinking involved in the original design. Mr. Wentworth-Sheilds had referred to the prevalent ignorance on the question of earth-pressures, and those who had that subject frequently before them—as he himself had, although on a very small scale compared with the work described in the Paper—would find it comforting to know that something definite was being done to provide information which would form a reliable basis for calculation. Was the factor of safety in the modified design as good as in the case of the original design? That question was not raised in any spirit of criticism, because risks could not be incurred in work of the kind in question if they could possibly be avoided, but it would be of interest to know whether the modified design had been adopted on account of any particular circumstances other than the difficulty of sinking, and whether it had given the same stability.

⁂ **Mr. E. M. Fitt** thought that it might be of interest to amplify the information already given by the Author in regard to some of the principal machinery used in the construction of the King George V graving dock. For the excavation in bulk, the Contractors had decided to use steam excavators, for the reason that, in their opinion, at that time steam was to be depended upon to a far greater extent than either petrol or diesel machinery for continuous work without breakdown. That decision had been taken with the knowledge that the fuel cost would be many times greater. The whole of the work was done by one No. 10 Ruston dragline

⁂ This and the succeeding contribution were submitted in writing.
—SEC. INST. C.E.

with a $1\frac{1}{4}$-cubic-yard capacity bucket and two Ransome dipper-bucket excavators with $1\frac{1}{4}$-cubic-yard capacity buckets, either of which could be converted for dragline work when required. The mud, gravel and clayey sand (commonly called greensand) was transported in steel tipping wagons of 11 cubic yards capacity, hauled by steam locomotives. The railway tracks for all excavation and concrete work were of 4-foot $8\frac{1}{2}$-inch gauge, with flat-bottomed rails weighing 70 or 75 lb. per yard. To consolidate the filled material behind the walls, diesel caterpillar-tractors were used, fitted as bulldozers to spread the material in layers about 4 inches deep. The excavation of the trenches, which were approximately 40 feet wide at the surface, was carried out as far as possible by means of heavy-type whole-tined Priestman grabs and 7-ton steam cranes fitted with double drums.

The central plant for washing gravel, and for concrete-mixing, was arranged to take advantage as far as possible of the natural differences of level of the ground on the old foreshore. The washing plant consisted of two large drums, each capable of handling 75 cubic yards per hour; a belt conveyor with a capacity of 120 cubic yards per hour raised the washed gravel to the overhead bins. The concrete was mixed in two Rex mixers of 1 cubic yard capacity each. The cement was transported in bulk from the works on the Medway in common-user railway trucks, the trucks being lined inside with steel sheets, and covered with two tarpaulins. It was interesting to note that no cement was spoilt in transit during the whole period of the contract. When concreting was in full operation, a train of wagons arrived every morning. The trucks were run into a high-level cement-shed, so designed that the cement could be shovelled out of the truck direct into large hoppers; the latter had only very small openings at the top, with the object of preventing pollution of the air by dust. That arrangement worked very well, and there was actually no more dust than in any ordinary cement-shed when large quantities of bags were being handled. The cement was conveyed by means of a horizontal screw conveyor and vertical bucket elevator to a bin over the mixers. For 6 months at the peak period a steady output of 10,000 cubic yards of concrete had been handled by that plant per week, working $10\frac{1}{2}$ shifts of 10 hours each.

While the floor was being concreted, an auxiliary plant had been rigged over the east dock-head, by means of which the output had been increased to a total of from 12,000 to 15,000 cubic yards per week. Cement was transported in $4\frac{1}{4}$-cubic-yard skips for the floor, and in $1\frac{1}{2}$-cubic-yard skips for the walls, both of the bottom-door type. The large skips were handled by 12-ton electric derrick-cranes, and the smaller ones by 7-ton steam travelling-cranes and by 7-ton electric derricks.

The following were some of the chief items of plant:—

Eleven 7-ton steam cranes.
Three 5-ton steam cranes.
One 15-ton electric derrick-crane.

Two 12-ton electric derrick-cranes.

Six 7-ton electric derrick-cranes.

Eighteen steam locomotives (mostly six-coupled, with 13-inch diameter cylinders).

The wall shutters were constructed of timber on the cantilever principle, 18 feet long by 5 feet deep, with legs extending vertically below. They were bolted to the concrete. A platform was attached to the legs to facilitate the removal of the bolts. The concrete floor was commenced at the entrance, and was constructed with a central block about one-third of the width of the floor, followed on each side by a side block. The central block was generally about 25 feet in advance of the side blocks. The shutters to form those blocks were constructed of timber. The ends of all three blocks and the sides of the central block were each made in one piece, which was lifted by a 12-ton derrick travelling on the finished floor. That crane had done most of the placing of the concrete in the floor.

Mr. W. T. Halcrow observed that the Author dealt very briefly with the layout of the important extensions of the port of Southampton, and referred to two schemes differing radically in principle, one embodying the jetty system and the other the continuous quay. It would be of interest if the Author were to give some of the reasons for the decision taken to adopt the long quay. In the absence of the views of the seamen who had to handle the largest vessels afloat, for which the quays were provided, he would be inclined to believe that the line which had been adopted would have the disadvantage of placing vessels at right angles to the prevailing winds, and that difficulty would arise in berthing and hauling off owing to the large surface presented to the wind. Had that difficulty been experienced? The advantages from the economic point of view of a continuous quay over jetties were well known. With the former ships could be moored bow to stern with no waste of quay-space, whereas in the latter system, with for example jetties 1,000 feet in length, one berth would normally be used by one vessel only, whether it was 1,000 feet long or only 600 feet long.

Before the War his firm had been asked to prepare schemes for the development of a system of docks at Keyhaven, on the flat land lying to the east of Hurst Castle; as an alternative to the extension of the dock system at the head of Southampton Water for large vessels, some advantages had been claimed. The site gave easier access for ships from the sea, and with deep water in the Solent immediately adjacent to the dock system, the necessity for extensive dredging, as was required in the channels to Southampton, would have been avoided. Railway connexion could have been made with the Lymington branch of the Southern Railway. An ocean quay was to have been incorporated so that vessels calling with mails and passengers could come alongside, instead of anchoring in Cowes Roads and being served by tender. Earlier in the century th

ean-quay scheme had reached a stage further than the dock scheme ferred to, in that powers had been obtained for an extension of the ilway and for the construction of the quay.

Many matters of interest were described in the Paper, not least of hich was the adoption of the well-point method of lowering the ground-ater level, both during the construction of the graving dock and per-anently. The sand to be drained appeared to have been sufficiently arse to allow the fine copper-mesh filter to work satisfactorily. If the nd had been very fine he doubted if that method would have been fective. When engaged on the construction of a large graving dock on e Tyne he had had experience of the difficulties encountered in building e foundations on wet running sand. In that case an attempt had been ade to lower the ground-water level by sinking cylinders to a depth low foundation-level, and then forming filters in the bottoms of the linders. The filters consisted of layers of coarse sand, with gravel and ushed stone and larger stone in layers above it, but the system had not roved satisfactory; the running sand was so fine that if the filters were ade of material sufficiently small to keep the sand out, the water would ot flow through. Ultimately the most difficult sections of that dock had een dealt with by boxing in the sand with cast-iron sheet-piling. Did the uthor consider that the filters for the well-points would have an indefinite fe, and if not, was there any method of renewing them? If that were ot possible, new wells would presumably have to be sunk to replace them.

The large masses of concrete placed in a comparatively short period ere bound to have contracted appreciably on setting. It would be of terest if the Author could give particulars of the steps taken to deal ith that matter.

In regard to the consolidation of the material forming the reclamation, Ir. Halcrow's experience was that settlement sometimes continued for a onsiderable period. Had any trouble been experienced? From the ections (*Figs. 7* and *8*, p. 194) it would appear that the buildings only ere carried on piles and that the railway, road, and cargo-shed floor ere carried on the filling.

The Author, in reply, thanked Mr. Wentworth-Sheilds for his personal eferences and for what he had said about the team of engineers engaged the work. Those who knew Mr. Wentworth-Sheilds would realize that he pleasure was not all on one side, and that it had been a very great leasure to serve under him.

Sir Henry Japp had referred to the relative merits of jetties and long uay-walls, and had said that he had heard that there was some difficulty berthing ships at Southampton alongside the quay-wall. It was quite rue that the jetty-scheme had many advantages, but the expert opinion f master mariners, marine superintendents of the various shipping com-anies, and the pilots, all of whom were consulted and with whom many eetings were held, was by no means unanimous on the side of the one

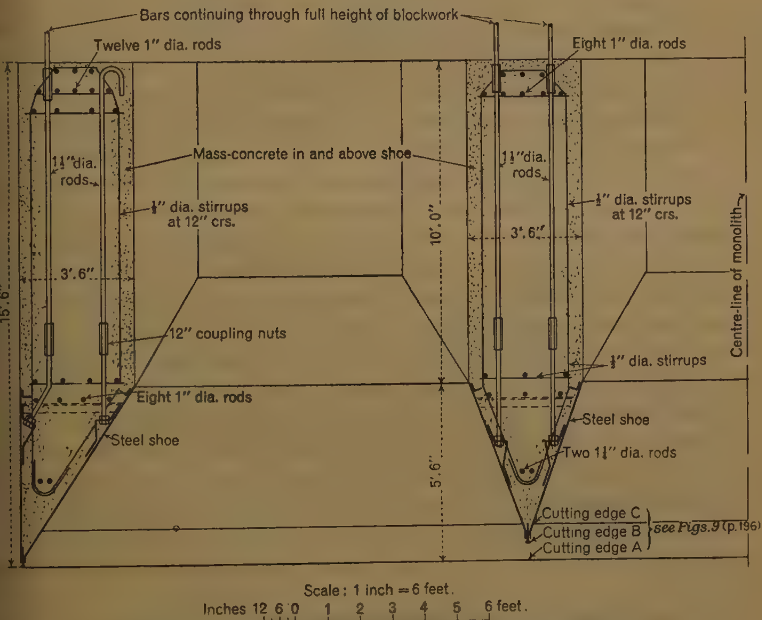
scheme or the other; that was why he had said in the Paper that t advantages of one appeared to outweigh those of the other, and they d The decision taken was, on the advice of the late Sir Frederick Palm reversed, but not so much from Sir Frederick Palmer's point of view th there was difficulty in navigating, as from the point of view that t long-dock scheme was more flexible than the jetties. The five jetties we to have been each 1,000 feet long, and ships could have been berthed each side of each jetty, thus providing ten 1,000-foot berths. It w considered, however, that there would never be ten 1,000-foot ships Southampton at the same time, and that the majority of ships berth would be more like 600 feet in length, so that the jetty scheme wou frequently mean using 1,000-foot berths for 600-foot ships, which was n strictly economical. It was much more flexible to have the long qu where the ships could be berthed stem to stern right along. So far difficulties of navigation were concerned, he thought that they were mo fancied than real; there had been only one occasion when a ship had be held on the quay through adverse weather-conditions. The idea that t long quay was not good from the point of view of handling ships w therefore, he thought, exaggerated.

He had been interested in Sir Henry Japp's description of the meth envisaged by his firm when tendering for the dock, and it would be interes ing to know whether that method—namely, the use of high-pressure je at the toes of the shoes—would have been effective. During the executi of the work, whenever difficulties had arisen in trying to deal with t greensand (which, incidentally, was not a pure sand but had an admixtu of clay with it), and to get it out from under the cant-plates, all kinds expedients, including the use of high-pressure jets, had been tried un Mr. Donald Mackenzie had invented the "scarifier" and the "surger Had it been pure sand, probably the high-pressure jets would have d persed it, but since there was an admixture of clay it seemed that th held the material together so that the jets merely bored a hole in it. T reinforcement in the monolith-shoes was shown in *Fig. 22*. The we were not always cleaned out by divers; occasionally, when it seem desirable, divers were sent down to inspect them, but generally speaki the wells were cleaned up by grabs.

In reply to Mr. Allen's question, the Author stated that there was limit laid down for the minimum permissible distance vertically betwe the monoliths, but no monolith being sunk was permitted at any time be more than 30 feet deeper than its neighbour. With regard to t horizontal distance between the monoliths, they were pitched, as stat in the Paper, 4 feet apart in the first half of the quay, and 7 feet apart the second half. The spaces were at times, of course, reduced and at oth times increased, by reason of the monoliths leaning towards, or aw from, each other during the process of sinking, and extreme care had to taken that the shoe of one monolith did not impinge on the wall of

ighbour. That was a matter to which the contractors had given a nsiderable amount of thought, and they had dealt with it successfully. ie usually accepted method of sinking a single monolith was that, if were high on one side, that side would be weighted while sinking was opped on the low side, and grabbing was continued on the high side; e monolith would then come back to a level position once more. With e monoliths at Southampton, however, possibly due to the nature of the ound and possibly to their size, they would not return to their correct

Fig. 22.



Reinforcement In and Above Monolith-Shoes.

osition in that way, and frequently in order to regulate the inclination nd to bring them back to a vertical condition once more it was necessary go three or four monoliths away and to sink two or three to ease them ack.

With regard to the cost of the work, to which Dr. Cunningham had eferred, the Author was in the same position as that in which most uthors probably found themselves. At Southampton it was particularly ifficult to give definite figures; for instance, if Dr. Cunningham asked ow much an acre it cost to reclaim the land, it would be possible to give im several correct answers! Similarly a number of correct answers ould be given for the cost per linear foot of the wall. The fact was that

there were several things bound up one with the other; it was necess
to dredge a deep-water channel and to dispose of the material, it w
necessary to reclaim land, and it was necessary to build a quay-wall, b
it was almost impossible to say how much of the expenditure should b
allocated to each of those three headings taken in isolation. For instan
some of the gravel obtained from dredging in the channel was used to fo
the main bank through which the monoliths were sunk, and some for co
crete in the quay-wall, graving dock, and other works; part of the ma
bank was subsequently dredged away and the material used for reclam
tion, whilst the gravel excavated from the bank during monolith sinki
was partly used for concrete in the quay-wall and partly for reclamatio
Unit prices under such circumstances might be misleading. As far as t
overall costs of the works were concerned, the money spent on them w
about £6¾ million. The graving dock cost about £1¼ million.

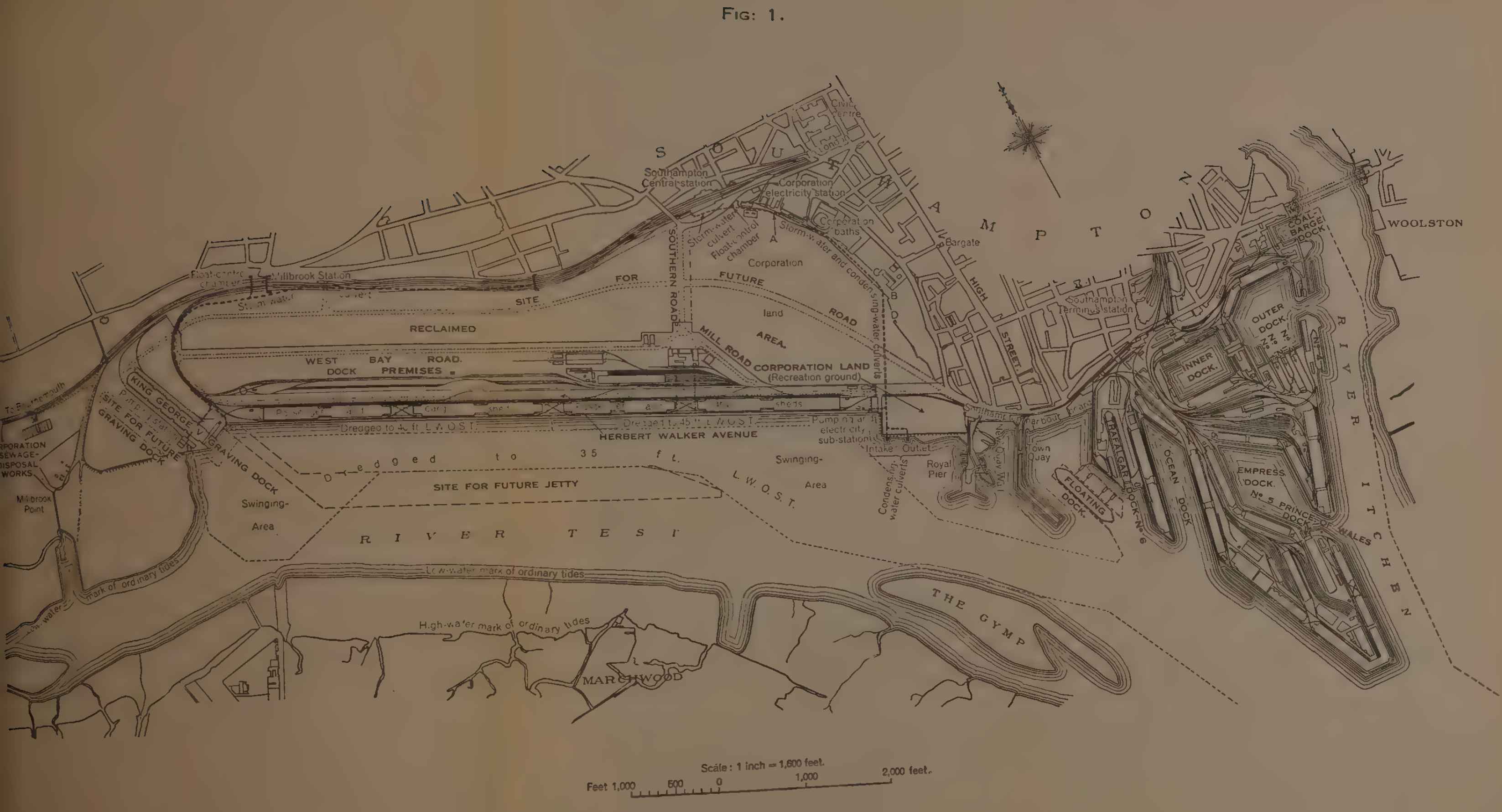
Dr. Cunningham also referred to the stability of the works and
similar works of lighter construction on the Continent and in Ameri
The Author had not seen the American works, although he knew them w
enough by repute, and from Dr. Cunningham's own books, but he thoug
that there was bound to be a critical point at which light work of th
kind ceased to be really economical. In deep water he gravely doubt
whether such light works were really economical. The walls provided
Southampton would stand without a penny of maintenance being spe
on them for many years to come, and that was something which could n
be said of timber-pile quay- or jetty-construction, at any rate in the wate
of Southampton. In the Weser at Bremerhaven, and at Bremen itse
he had seen quay-walls built with timber piles in a very cheap manner, b
it would be impossible to do that at Southampton, and no doubt at a gre
many other places also. He was not decrying for one moment wh
Dr. Cunningham had said, because he thought that there was a good de
in it, and the Southern Railway had often wished that they could bui
such works.

The accumulation of mud in the dredged berth alongside the qua
had not been excessive. It had been necessary to do maintenance-dredgi
there, but no more there than in any other part. What the future wou
show he did not know. It might be that in time the banks and the co
ditions generally would have stabilized themselves and that there wou
be still less to do. There had been no settlement of the monoliths anywhe
so far as it had been possible to ascertain.

*** The Correspondence on the foregoing Paper will be published in th
Institution Journal for October, 1938; the Author, in his reply theret
will deal further with certain points raised in the Discussion.—Sec. Ins
C.E.

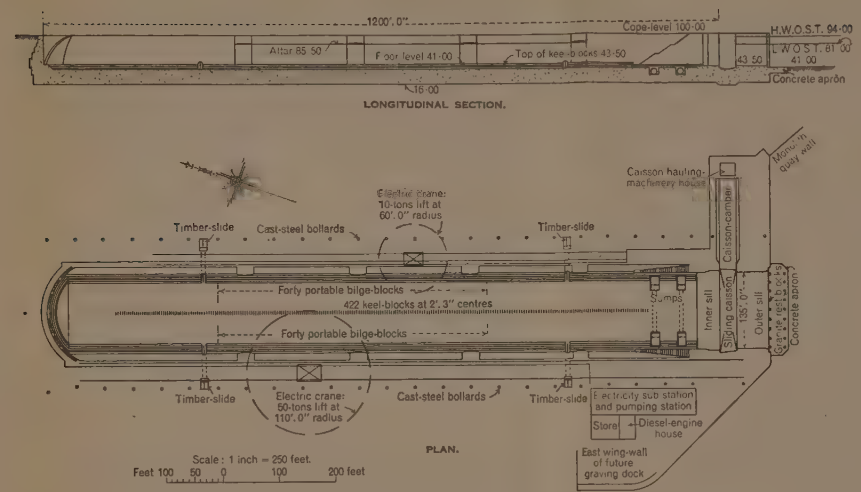
SOUTHAMPTON DOCKS EXTENSION.

Fig: 1.



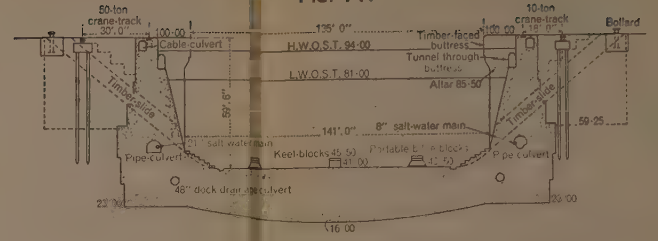
PLAN OF DOCKS EXTENSION AND EASTERN DOCK ESTATE.

Figs: 10.



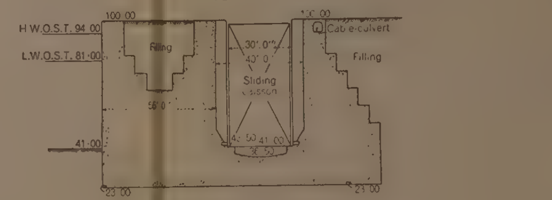
KING GEORGE V GRAVING DOCK: GENERAL ARRANGEMENT.

Fig: 11.



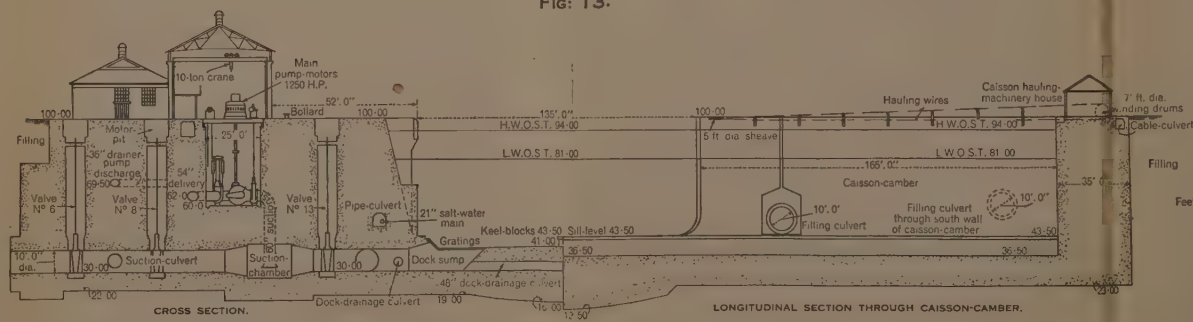
KING GEORGE V DOCK: TYPICAL CROSS SECTION.

Fig: 12.



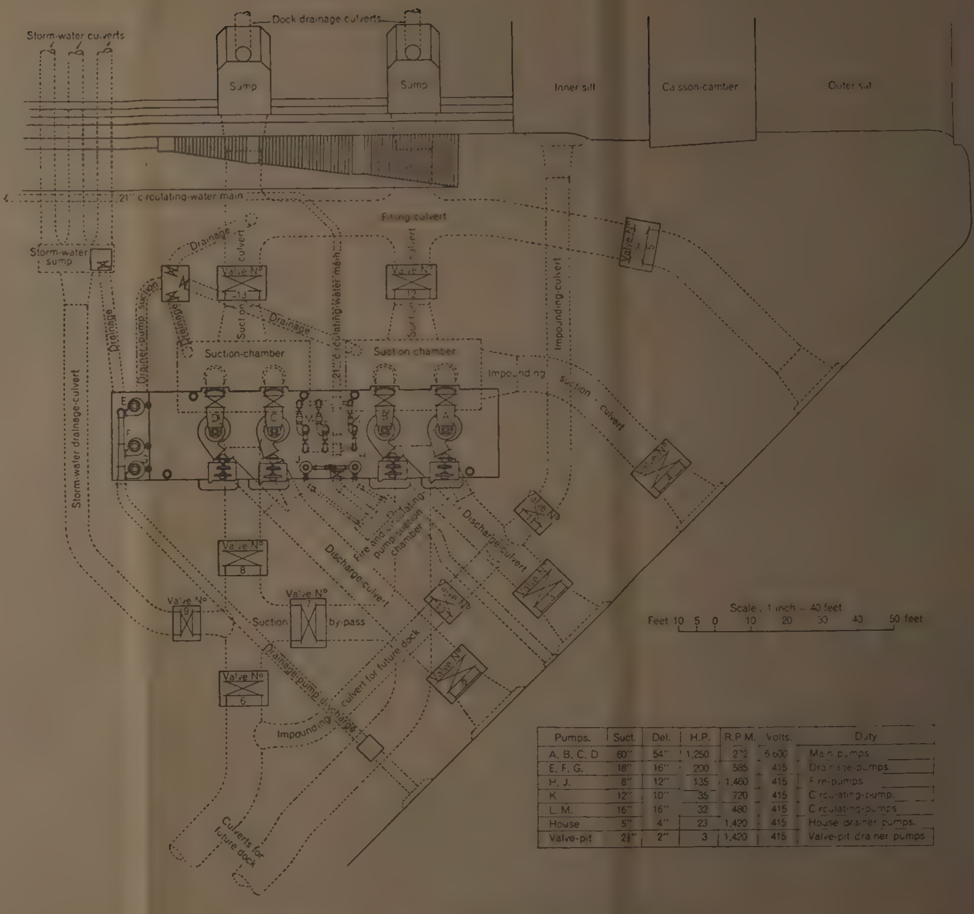
KING GEORGE V DOCK: CROSS SECTION THROUGH CAISSON-CAMBER.

Fig: 13.



KING GEORGE V DOCK: CROSS SECTION THROUGH PUMP-ROOM, AND LONGITUDINAL SECTION THROUGH CAISSON-CAMBER.

Fig: 17.



Pumps.	Suct.	Del.	H.P.	R.P.M.	Volts.	Duty
A, B, C, D	60"	54"	1,250	272	6,600	Main pumps
E, F, G.	18"	16"	200	585	415	Drainage-pumps.
H, J.	8"	12"	135	1,460	415	Fire-pumps
K	12"	10"	35	720	415	Circulating-pump.
L, M.	16"	16"	32	480	415	Circulating-pumps
House	5"	4"	23	1,420	415	House drainer pumps.
Valve-pit	2½"	2"	3	1,420	415	Valve-pit drainer pumps

PUMP-FLOOR AND CULVERTS ON WEST SIDE OF GRAVING DOCK.

M. G. J. McHAFFIE.

William Clowes & Sons, Limited, London.

EXTRA MEETING.

3 May, 1938.

SYDNEY BRYAN DONKIN, President, in the Chair.

PRESENTATION OF THE JAMES ALFRED EWING MEDAL.

The President said that the James Alfred Ewing Medal had been unded in 1936 in memory of Sir Alfred Ewing, who died in 1935 and who is an Honorary Member of The Institution. The endowment fund had en contributed jointly by Lady Ewing, whose generosity was most ncerely appreciated by The Institution, and by friends and admirers Sir Alfred Ewing, and the income accruing from that endowment was ent in the provision of a gold medal, together with a bronze replica, for ward to a person, whether a member of The Institution or not, for ecially meritorious contributions to the science of engineering in the field research.

The present was the first award of the medal made by the Council. In cordance with the wishes of the joint founders, the award had been ven on the recommendation of the President of The Institution of Civil ngineers, in the present case Sir Alexander Gibb, and of the President the Royal Society, Sir William Bragg. The selection had been made ter consideration of personal recommendations for the award by the residents of the Institutions of Mechanical Engineers, Electrical Engineers, nd Naval Architects, together with the Vice-Presidents of The Institution Civil Engineers.

The award in the present instance had been allotted to Mr. Charles amuel Franklin. Mr. Franklin received his engineering and scientific aining at Finsbury Technical College, under Professor Sylvanus Thompon. After some time spent in general electrical work, he joined Marconi's Vireless Telegraph Company in 1899. He had been closely associated ith wireless development in England since that date, the most outstanding nventions and developments to his credit being :—

(i) The multiple tuner and other inventions in connexion with early wireless receivers.
(ii) Reaction patents in wireless-receiver circuits.
(iii) The early English broadcasting stations, including 2LO, London.
(iv) Directional receiving systems for long-wave communication.
(v) Rotating beam aerials.

(vi) Short-wave wireless transmitting and receiving circuits.
(vii) The Franklin beam aerial, which was the fundamental inventi
in connexion with the Marconi beam system.
(viii) The concentric-cable system, which enabled high-freque
currents to be transmitted with minimum loss, and
essential for television transmission-circuits.

It was in consequence of the great value of Mr. Franklin's researc in the science of light electrical engineering, and of their subsequ developments during the last 35 years, that Mr. Franklin had b unanimously recommended for the award. He had, therefore, gr pleasure in asking Mr. Franklin to accept the first James Alfred Ew Medal and in expressing to him the congratulations of the joint Insti tions represented in connexion with the award.

Mr. C. S. Franklin expressed his thanks to Sir Alexander Gibb, Sir William Bragg and to the Council of The Institution of C Engineers for honouring him by the award of the James Alfred Ew Medal. He had, he said, worked for nearly 39 years with the Marc Company in connexion with the development of wireless communi tions, and it was a great pleasure to him to receive that proof th his work had been recognized outside that organization. At the sa time, he desired to acknowledge his indebtedness to the late March Marconi and to the Marconi organization for the opportunities that he h had, and to the many colleagues who had worked with him. He wou also like to thank the President of The Institution for his very kind remar

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THE JAMES FORREST LECTURE, 1938.

The President mentioned that the James Forrest Lecture w established and endowed in honour of Mr. James Forrest, who had bee Secretary of The Institution from 1859 to 1896 and Honorary Secreta from 1898 until his death in 1917. The present Lecture was the fort fourth of the series. In accordance with Mr. Forrest's desire, vario pieces of presentation silver received by him from societies and individua during his term of office as Secretary were exhibited outside the lectu theatre.

The Council were very gratified that Sir Frank Smith had accept their request to give the present Lecture; his subject would be "Di orderly Molecules and Refrigerating Engineering." Sir Frank was we known as Secretary of the Royal Society and Secretary of the Departme of Scientific and Industrial Research, and he was glad to say that S Frank was also an Honorary Member of The Institution. It gave hi great pleasure to call upon Sir Frank Smith to deliver his Lecture.

"Disorderly Molecules and Refrigerating Engineering."

y SIR FRANK EDWARD SMITH, K.C.B., C.B.E., D.Sc., LL.D., F.R.S., Hon. M.Inst.C.E.

INTRODUCTION.

r WILLIAM BRAGG, the James Forrest Lecturer of last year, explained w the structure of every crystal contains the solution of an engineering oblem. He pointed out that the atoms of which crystals are made are ld together by forces which so operate that the atoms are grouped gether in some regular geometrical pattern. In his inimitable manner r William Bragg pointed out that this study of the way in which atoms range themselves is of great interest to the engineer, inasmuch as every bstance used by him to build structures is more or less crystalline in aracter, and its properties depend on the orderly manner in which the oms are held together.

My Lecture this evening touches on another branch of atomic behaviour. hope to interest you in the disorderly movements of atoms and mole-les. There is, I think, little doubt that, just as nature in the inorganic orld arranges the atoms in crystals to form substances having diverse operties, and in the organic world builds up groups of atoms to fulfil finite functions in plant and animal life, so the disorderly movements atoms and molecules are designed primarily to facilitate changes of mposition and structure and to be the main agent in the transmission heat and power.

In the same way as the engineer has measured toughness and hardness iron and steel without associating these properties with the orderly ouping of atoms, so has the engineer, by the decomposition of coal, oduced heat to raise steam and afterwards to produce power, without ore than a passing thought of the disorderly movements of the molecules which these changes depend.

These disorderly motions, whether the substance be solid, liquid or seous, represent definite amounts of mechanical energy, and it is on the ypothesis that this energy is identical with heat that thermodynamics d mechanics become united. With this conception of the nature of at, it follows that the quantity of heat in a substance is a measure of e total kinetic energy of the molecules, and temperature is a measure the intensity of their translatory movement. When the movement is ro the temperature is also zero on the absolute scale. In recent years e of the great advances in science has been the attainment of very low mperatures; that is, the slowing down of molecular motion. Indeed, mperatures on the absolute scale of not more than a few thousandths of degree have been reached, and the properties of materials at these

temperatures are being studied. With this increase of knowledge an better understanding of the motion of liquid molecules and the evapora of liquids, there has been a corresponding advance in engineering techni and gradually but surely there has arisen the new industry of refrigera engineering. This new industry is a direct consequence of our gre knowledge of the properties of molecules in motion, and I have there coupled refrigerating engineering with the main title of my Lecture.

Although still in the infancy of its development, refrigeration already entered almost every phase of human activity. The Great emphasized its value for preserving food; indeed, its use for preserv fruit, vegetables, and meat is extending year by year as we find out m about the biological nature of the things we eat. In civil engineer refrigeration is employed for tunnelling and mining work; the chem engineer uses it to extract nitrogen from the air and hydrogen from co oven gas, and thereby obtains the elements needed for the synthesis ammonia; the mechanical engineer uses for oxy-acetylene welding oxy obtained from the air by refrigeration; the electrical engineer empl argon and neon, similarly extracted, for illumination-purposes; whilst air-conditioning of public buildings, staterooms in large steamships, railway-trains in tropical climates relies much upon refrigeration for efficiency. To the non-technical mind, refrigeration implies ice-crea and it is of interest to note that the United States of America prod over 180 million gallons of ice-cream every year.

Kinetic Theory of Molecular Motion.

I do not propose to deal with the historical aspect of the subje nor shall I approach it from a mathematical standpoint. Instead shall endeavour to explain the phenomena associated with refrigerati by consideration only of the nature of molecules, their movements a their interactions. Such conceptions may be mere approximations to t truth, but, having regard to the number of phenomena for which they c provide a satisfactory explanation, I think we may accept them sufficiently trustworthy for our purposes.

Every engineer is acquainted with Boyle's law, and its modified form connecting the pressure and volume of a gas. It is, however, well remember that none of these equations is based on a quantitative kno ledge of the electro-magnetic properties of atoms; yet there is little dou that it is because of these electromagnetic properties that atoms sometim attract and sometimes repel one another. Indeed, the equations a based on data obtained from experiments on atoms in bulk, and not isolated atoms.

Let us consider for a moment the molecules of oxygen, nitrogen, carb dioxide, argon and other gases in this room. If they were reduced to t absolute zero of temperature, all the atoms and molecules would

rfectly still, and gravity would cause them to fall to the floor. At esent, although of course gravity acts on them, the molecules of oxygen this room move, on an average, at a speed of about 50,000 centimetres r second. Their motion is disorderly. They move in all possible rections, colliding with one another, with the molecules of nitrogen, gon, etc., and with the walls of the room. If the temperature conditions tside the room remain the same as those within, this disorderly motion ould never diminish in intensity, for molecular motion does not become graded. The disorderly motion is, as I have already stated, heat itself, d although gravity is continually acting on the molecules, the only ect of gravity is for the velocity upwards to be slightly less than the locity downwards. Such disorderly motion is most manifest in gases, a lesser extent in liquids, and to a still smaller degree in solids.

oms and Molecules.

In the kinetic theory of gases it is usual to think of an atom of a gas an infinitely small particle having no volume. An alternative is to ink of it as a sphere like a billiard-ball, but of very small size. Such nceptions, although useful, are not sufficient for my purpose this evening. must ask you to take a more modern view. The atom is not a sphere; believe that all atoms contain a nucleus which is charged with positive ectricity, and that around the nucleus there are electron shells. The ace between the charged particles is great compared with the size of a rticle, so that an atom is largely empty space. We may assume that e number of electrons associated with every atom is equal to the number unit positive charges in the nucleus, so that, taken as a whole, the om is neutral. It may be that the electrons move round the nucleus the planets move round the sun, or the motion may be of a more com-ex nature; it is possible that each electron forms a sort of gaseous or jellified" loop around the nucleus. While, for my purpose, the exact ture of the movements is not very material, it is important to emphasize at the atoms and molecules are largely empty spaces. When collision kes place it should be possible for one atom to pass through another, d even if it does not do so the stresses set up are of quite a different aracter from those resulting when two billiard-balls collide.

The distribution and behaviour of the electrons are matters of great portance, but I cannot deal with them in this Lecture. However, it is interest to note that on them depend the optical, chemical, electrical d magnetic properties of the atom; the properties of the individual oms are largely reproduced in atoms in bulk, and it is material in bulk hich the engineer uses in his structures. While, however, something is own of the distribution of the electrons, precise knowledge has not been tained. We do know, however, that the atoms have internal degrees freedom, and it is to these that we must turn for explanations of many ysical phenomena.

The space in which the nucleus and electrons perform their motio may be taken as equal to that of a sphere about 1×10^{-8} inch in diamet It will, however, be apparent that such atomic structures scarcely all their size to be exactly defined. As we shall see later, when two atoms a side by side in equilibrium and in apparent contact, as in a liquid, all th is implied is that certain attractive and repulsive forces balance. W know that by applying pressure the atoms can be forced nearer togethe

In solids the vibratory motion which constitutes heat is due to t vibration of the atoms only, and not that of complete molecules. T atoms in many simple substances, such as sodium chloride and potassiu chloride, have been shown to be so placed that they are linked to neig bouring atoms in precisely the same way, the structure rendering it dif cult, if not impossible, to imagine a rigid molecular combination. Indee the atoms appear to be independent units. The atoms in a solid can on travel about their mean positions, and the distances travelled are minu in extent unless there is some form of disruption. Disruption occurs the temperature increases beyond a certain point, for with increase temperature the average vibratory energy of the atoms increases, a ultimately many atoms break away from their equilibrium positions a do not return. Instead they occupy new positions of equilibrium a vibrate about new centres, but even so only temporarily. This chan in relative positions results in the body becoming plastic. When there constant re-arrangement of positions and the energy of vibration is grea the substance becomes liquid. The forces between the atoms now resu in their combination to form molecules, and in liquids it is not the atom but the individual molecules which vibrate. They thread their wa through their neighbours, and at the surface, if the temperature is suf ciently great, the more energetic molecules break away from their neig bours, and evaporation results. In the new gaseous state, the atoms st remain in combination to form molecules, and it is the vibration of t molecules which constitutes heat.

Distribution of Energy.

In the case of any molecule consisting of more than one atom, it conceivable that when energy is given to it, whether in the form of he or otherwise, the energy absorbed may be accounted for by (1) an increa in the kinetic energy of molecular motion in straight lines, (2) a displac ment of the atoms within the molecule, (3) an increased rotational ener of the molecule, or (4) the setting up of electromagnetic stresses with it or the constituent atoms. However, my purpose this evening is n the study of all these complex motions but the association of the straigh line motion with problems of refrigeration. Except for this passing refe ence to rotational energy and stress-energy contained within the molecu itself, I shall therefore limit my remarks on energy-transformations to t translatory motion of the molecules and to changes of kinetic energy in

tential energy. In the case of monatomic gases like argon the bulk of e molecular energy is in the kinetic form.

ranslatory Motion.

I have spoken of the molecules of gas in this room and have referred the fact that the average intensity of their translatory motion is a easure of the temperature. The air of this room consists of molecules many gases, including oxygen, nitrogen, argon, carbon dioxide, and ater vapour.

The average diameter of a molecule of this mixture is about 3×10^{-8} ntimetre; the average speed of movement is about 50,000 centimetres r second, and the average distance apart is such that 1 cubic centi-etre contains about 3×10^{19} molecules. The mass of a molecule is about $\times 10^{-23}$ gram.

The kinetic energy of a molecule in motion is proportional to its mass d to the square of its velocity, but notwithstanding the variation in ass of the molecules which constitute air, the average kinetic energies of e different kinds of molecules are equal. In practice the lighter molecule oves faster than the heavier one.

It is customary to think that the molecules of a gas at normal atmo-heric pressure and temperature are much further apart than the mole-les of a liquid. This, however, is not so. Under ordinary conditions temperature the density of a substance in the solid or liquid condition about 1,000 times as great as the same substance in the gaseous con-tion, and the average distance apart of the molecules in a gas may erefore be taken as being roughly 10 times as great as in the solid or quid. The molecules of air in this room are roughly 10 diameters apart; at is, approximately 3×10^{-7} centimetre apart. They move in straight nes with an average velocity of the order of 50,000 centimetres per cond, and since neighbouring molecules are about 10 diameters away, is not surprising that a molecule collides with a neighbour for about ery 300 diameters of travel. The average distance travelled between vo consecutive collisions is about 1×10^{-5} centimetre, and every mole-ule collides with another or with the walls of the room about 5,000 million mes a second. When two molecules collide the collision changes, in eneral, the direction of movement of both, and they also assume new elocities. It is such disorderly movements of comparatively empty aces that are of such great importance to the engineer, and without em modern refrigerating engineering could not exist.

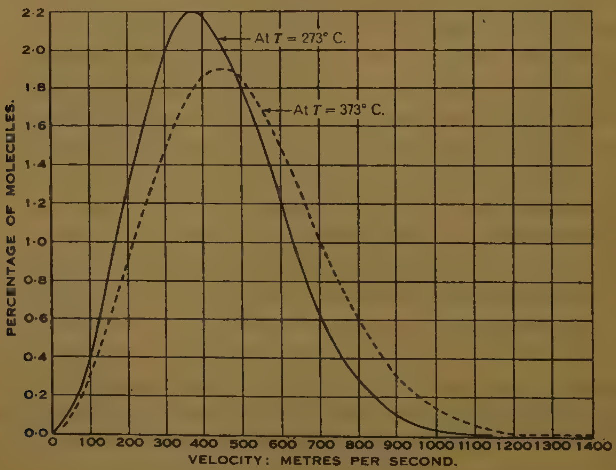
At any particular moment it is most unlikely for all the molecules in his room to possess the same kinetic energy. Collisions alone would revent such a thing. Yet normally the air of this room would be regarded s being in a steady state. However, this only means that no change can e detected by our senses with or without the aid of ordinary instruments. ut the velocities of the individual molecules do in fact vary, and the

term "steady state" only implies that the general limits of variation not change, not that the energy of any particular molecule does not var Maxwell's law of the distribution of velocities tells us how many molecu of a gas at any particular instant possess a certain velocity or are with certain limits. Thus, for oxygen at 0° C.—

Velocity.	No. of molecul per cent.
Below 10,000 centimetres per second	1·4
Between 10,000 and 20,000 centimetres per second	8·1
,, 20,000 ,, 30,000 ,, ,, ...	16·7
,, 30,000 ,, 40,000 ,, ,, ...	21·5
,, 40,000 ,, 50,000 ,, ,, ...	20·3
,, 50,000 ,, 60,000 ,, ,, ...	15·1
,, 60,000 ,, 70,000 ,, ,, ...	9·2
Above 70,000 centimetres per second	7·7

Fig. 1 gives the percentages of molecules having velocities with successive limits of 1 metre per second, and the average velocities metres per second.

Fig. 1.



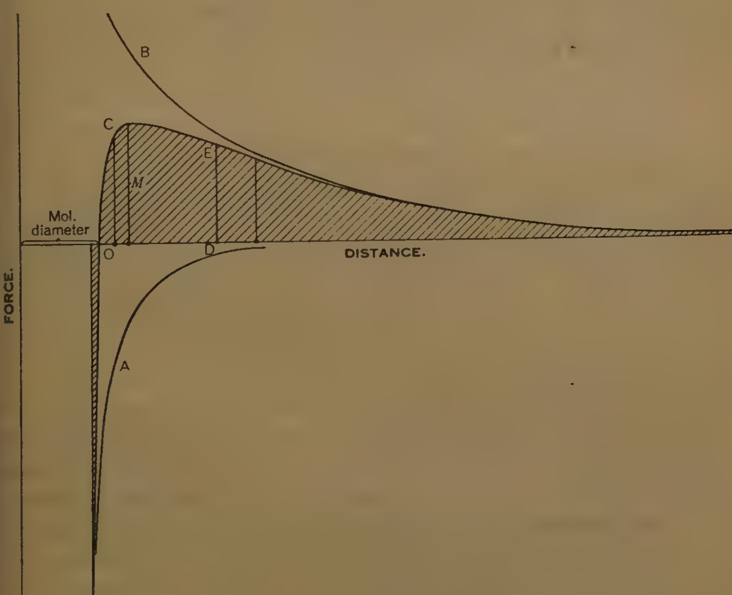
Collisions between Atoms and Molecules.

Let us consider a single atom, with its one or more shells of electron being suddenly struck by another one travelling at an enormous spee Normally, two similar atoms would lie peacefully side by side, neith intruding into the domain of the other, for although in bulk each atom electrically neutral, its parts are definitely electrically charged, and the is opposition to the entry of other charged particles. When, howeve one atom is hurled at another at an enormous velocity, the resistance

trusion may be overcome and the atoms may pass through each other. this passage some loss of electrons may arise, either temporarily or rmanently. However, the atoms of oxygen and nitrogen in this room, though they are travelling at about 50,000 centimetres per second, are ot moving, in my sense of the word, at an enormous speed; the velocity indeed, comparatively sluggish compared with that necessary for inter-netration of parts. In practice, at present, the engineer is not concerned ith changes involving the loss of electrons.

When two atoms or molecules collide or approach very near to one other, a different kind of disturbance is set up. It may be that the ectronic paths are disturbed, thus producing an electro-magnetic stress. rtainly some stressed condition results, and the stress is probably electro-

Fig. 2.



agnetic in character. If we imagine that two atoms collide and that, r a very small fraction of time, both are stationary, then the kinetic nergies will have disappeared and the electro-magnetic stresses will multaneously have reached their maximum values; afterwards the ressed systems cause repulsion to take place, and the atoms move away om one another. If, therefore, either by violent impact or some other eans, two atoms get very close together, stresses will be set up and there ill be some conversion of kinetic energy into potential energy. The urve connecting the force of repulsion and distance is probably some-ing like curve A (*Fig. 2*), in which the ordinate represents the force and

the abscissa the distance between the centre of the atoms. If two atom of different substances collide, the stresses may be so great that som form of union results. In other words, there is chemical combinatio It is not surprising, therefore, that chemical reactions are promoted b increasing the temperature and that at very low temperatures man substances are inert.

Attractions between Molecules.

Atoms and molecules also attract one another, as otherwise they wou never condense to form liquids and solids. This attraction is possibly the nature of electro-magnetic induction, but again precise knowledge not available. The average kinetic energy of the liquid molecules boiling water is about the same as the kinetic energy of the molecules water vapour, or steam, above the surface. The water molecules and th molecules of steam are, we know, at about the same temperature. I water at ordinary temperatures the vibrating molecules thread their wa through the liquid and some with more than average energy leave at th surface. Thus evaporation takes place. To tear the molecules apa requires work to be done, and this is supplied in the form of heat. If n heat is added the average kinetic energy of the liquid is lowered. Th latent heat of evaporation is thus a measure of the energy required t tear the molecules apart. This attractive force falls off with distance ; th curve connecting the force of attraction and the distance between th molecules is probably of the form shown by the curve B (*Fig. 2*).

Resultant Force on Molecule.

If the two curves A and B (*Fig. 2*) are to scale, the net result of th attractive and repulsive forces is the curve C. At O, the force betwee the two molecules is zero ; in other words, the molecules are in equilibrium and the substance is, in general, a liquid or a solid. The distance betwee the molecules can be changed by pressure ; an increase will diminish th distance and a decrease will cause the molecules to move further apart Hence the slope of the curve C where it crosses the axis at O is a measur of the elasticity of the material.

Since the relationship between the change of force with distance from O is not linear, it follows that increase of the vibrational energy mus result in some displacement of the centre of vibration. Thus a molecul requires a greater force to move it a distance dx towards another molecul than to move it the same distance away from it. As a result, if th amplitude of vibration be increased to $2dx$ the centres of vibration o the molecules will move apart ; in other words, expansion will follow a increase of temperature.

The position of maximum height M of the curve C is also of interest for it represents the maximum force which could be applied to the solic

ithout rupture. If the stretching force be less than this maximum, en on release of the force the molecules will snap back to their previous sitions. If, on the other hand, the force exceeds M slightly, the solid retches until rupture occurs. The point where M cuts the axis repre-nts, therefore, the elastic limit of the substance. In practice, bulk aterial, as used by the engineer, is imperfect, containing either holes or clusions of foreign materials; these cause the elastic limit to have a uch lower value than would result if the body were pure and homo-neous.

Let us suppose that the substance is liquid, and that some of the olecules in the neutral position O were removed by force from their ighbours to form a gas. The force would vary with distance and would e proportional to the ordinate of the curve. Hence the work done in moving a molecule to the position D would be proportional to the shaded ea ODEC. If the ordinate DE is very small, as it would be if OD were ore than a few molecular diameters, the shaded area would be proportional the ordinary latent heat of evaporation.

The Joule-Thomson Effect.

If a gas is at high pressure and is allowed to expand, the molecules ill separate and work must be done. The energy is taken from the inetic energy of the molecules and the gas is therefore lowered in tempera-ure. The heat or energy thus absorbed from the gas is converted into otential energy represented by a change in the electro-magnetic stress in he molecules. This cooling action on expansion, known as the Joule-Thomson effect, is used to-day in many commercial processes for cooling ases, and in some cases for liquefying them. We shall see later that xceedingly low temperatures are in practice attained in this way.

Such a presentation of the case is not, however, complete. The mole-ules are not only in constant motion, but are in continual collision with ne another, and these collisions result in electro-magnetic stresses being et up. Thus the energy of a number of molecules is divided into two arts: one is kinetic energy, the average intensity of which is a measure f the temperature, and the other is the potential energy represented by he electro-magnetic stresses set up by collisions. If we imagine, at a articular instant of time, all the molecules of a gas to be in collision and tationary, the electro-magnetic stresses would be at their maximum, and he kinetic energy would be zero. The whole gas would, for a small nstant of time, be at the absolute zero of temperature. The next instant epulsion between the molecules would take place and the kinetic energy would rise to maximum value and corresponding maximum temperature. n practice, of course, such exceptional conditions do not arise in a mass of gas; instead, there is an average condition. It is, however, because of this continual transformation of part of the kinetic energy of the mole-

cules into potential energy, and *vice versa*, that a gas on expansion ten to be heated. Thus, when the volume of a gas is doubled, the numb of collisions per second is halved, and whatever the average potenti energy was before, the amount will now be one-half; on the other han the average intensity of the kinetic energy will be greater and the temper ture is correspondingly increased. If, before expansion, the temperatu were increased, the potential energy per impact would also increase an the fall in potential energy on expansion would be greater than befo In other words, the effect is more marked with increase of temperature.

In every gas there are therefore two effects on expansion, one tendi to cool the gas and the other tending to heat it. The cooling effe depends on the degree of separation of the molecules. The heating effe depends on collisions and increases with increase of temperature. I consequence, in all gases at sufficiently high temperatures the net effe of expansion is a rise in temperature. At a temperature known as th inversion-temperature there is no change, and below it there is a fall temperature on expansion.

Joule-Thomson Refrigerators.

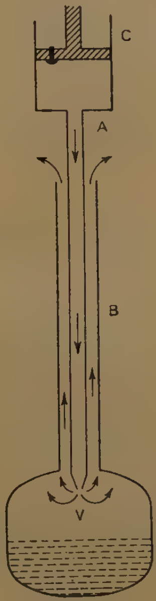
The Joule-Thomson effect is by no means small. If molecules of a are about 2 diameters apart and they are separated so as to be 10 di meters apart, they lose about 15 per cent. of their kinetic energy. the fall in pressure is from 200 atmospheres to 1 atmosphere, the coolin effect is about 40° C. It would appear, therefore, that to liquefy air, which the main constituents boil at —183° C., and —196° C., a fall i pressure of about 1,000 atmospheres would be required. However, i practice, expansion to atmospheric pressure is rare, for whilst the coolin produced depends on the fall in pressure, the work done in compressing gas is proportional approximately to the logarithm of the ratio of the ai pressures. Again, liquefaction of air by compression alone is impossib at ordinary temperatures, for the air must be below the so-called critic point, which for air is —141° C. Hence some preliminary cooling necessary.

Very high pressures and very low initial temperatures are, howeve unnecessary. About the same time as the Joule-Thomson effect wa discovered, a device known as a cold-regenerator or heat-exchanger wa invented. In general, this consists of a series of closely-coiled tube through one of which the compressed gas proceeds on its way to th expansion-nozzle, and through another in close thermal contact with th first the relatively cold expanded gas returns. The oncoming gas is thu progressively cooled. Diagrammatically the complete process of coolin by the Joule-Thomson expansion-effect and regenerative cooling is show in *Fig. 3*. The gas from the compressor C proceeds down the tube A, i expanded at the nozzle V and is thereby cooled. The cold expanded ga passes upwards through the tube B which surrounds A and thus cools th

coming gas in A, which in turn is expanded and further cooled. This ogressive cooling continues until part of the gas liquefies and collects D. At the same time stable gradients of temperature are established the two tubes.

The first commercial machines to be constructed on these principles

Fig. 3.



ere by Linde and by Hampson. With such machines liquid air can be roduced within a few minutes from starting-up.

The Claude Expansion-Method of Liquefaction.

A compressed gas is necessarily cooled when, by expansion in an ngine, it does external work. The bombardment of the rapidly moving molecules of gas on the piston constitutes the pressure, and as the piston moves forward and does work, some of the kinetic energy of the molecules s transformed into external work. The temperature of the expanding gas is thus lowered.

This principle was applied by Claude. The gas to be liquefied is compressed and cooled by water or air. Part of it then passes into an engine, does work by expansion, and is thereby cooled. It then passes into a condenser, in which it serves to cool and liquefy another part of the gas from the compressor, a heat-exchanger being employed. As with the Joule-Thomson apparatus, it is essential for the temperature of the con-

denser to be lower than the critical temperature of the substance if th gas is to be liquefied. To liquefy air necessitates the compressed gas the engine being at a very low temperature. In practice it is abo —120° C. In consequence, lubrication troubles were at first experience They were overcome by Claude by using petrol ether mixed with cylinde oil as a lubricant until liquid air was formed, when the liquid air itse served as a lubricant.

In the liquefier designed by Kapitza, who adapted the Claude metho for the liquefaction of helium, a small gap was left between the pisto and cylinder, so that the two are never in contact and no lubricant therefore required. Loss of gas through the gap is minimized by workin the piston at a rapid rate. The cooling by Kapitza's expansion-engi can be carried below 10° K.

Pure Gases by Rectification.

When the demands for liberal supplies of oxygen for medical an industrial purposes first arose, the demands were met by a chemic process, namely, the oxidation and de-oxidation of barium oxide. It wa not until the end of the nineteenth century that Linde and Hampso produced machines for liquefying air and other gases by the Joul Thomson effect. By itself, however, this method cannot separate oxyge from the air; it merely liquefies the air, and the resultant liquid is mixture of oxygen, nitrogen, argon, and traces of other gases.

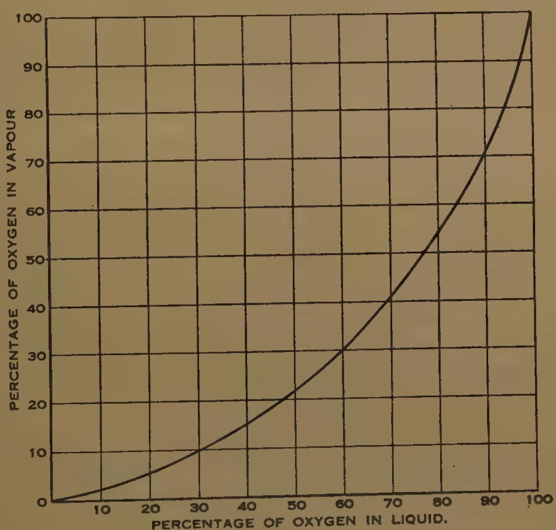
While liquid air is of some service, the main demand in engineering for comparatively pure oxygen for welding and other purposes, and fo nitrogen for the manufacture of ammonia and cyanamide. It becam necessary, therefore, to separate the oxygen from the nitrogen. We sha see later that argon is also of considerable importance.

The process adopted for separating the gases is known as rectificatio being analogous to that used by distillers for extracting alcohol fro fermented wort.

Rectification depends on the fact that when equilibrium exists betwee a mixture of two liquids and the vapour it gives off, the composition the vapour is always different from the composition of the liquid if th two liquids have different boiling-points. The substance which has th lower boiling point (that is, the one which is the more volatile) is in great proportion in the vapour than in the liquid. Oxygen boils at 90° K and nitrogen at 77° K., and in liquid air there is approximately 21 pe cent. of oxygen and 79 per cent. of nitrogen. The liquid nitrogen is th more volatile, and when equilibrium results between the liquid air an the vapour above it, there is about 7 per cent. of oxygen and 93 per cen of nitrogen in the vapour. *Fig. 4* gives the relation between the pe centage of oxygen in a liquid mixture of oxygen and nitrogen and th percentage of oxygen in the vapour in equilibrium with it.

Diagrammatically, the separation of oxygen and nitrogen by rectifica-
n is shown in *Fig. 5* (p. 252). From the upper vessel drops of liquid air l slowly towards the lower vessel, which contains liquid oxygen. Vapour given off from the latter, and as the molecules come into close contact th the drops of liquid air, some of them condense, since the liquid air is a lower temperature. Part of the nitrogen in the drops evaporates nultaneously, with the result that if the drops are small and they fall ry slowly, all the nitrogen is evaporated by the time they reach the wer vessel. Oxygen alone is left. The gas leaving the upper portion of e tube is shown as having a composition of about 7 per cent. of oxygen

Fig. 4.



ad 93 per cent. of nitrogen, this being the composition of the vapour in quilibrium with a liquid having the same composition as air. In ractice, this vapour, which is under pressure, is allowed to expand, and expanding it liquefies at the temperature of the liquid oxygen. This quid, if allowed to fall in drops as before, will cause more oxygen from ie ascending vapour to condense and more nitrogen to evaporate, with he result that the gas gets richer and richer in nitrogen.

ndustrial Uses of Oxygen, Nitrogen and Argon.

In such manner comparatively pure oxygen, nitrogen and argon are btained from the air. Such supplies have not only opened up new fields f research, but have created new industries. Oxy-acetylene welding is

now in common use for the manufacture of boilers and tanks, and almo[illegible] all the commercially-used ferrous and non-ferrous metals can be weld[illegible] by its use. Steel and cast iron can be oxygen-cut by hand, and, giv[illegible] fair visibility, the cutting of steel under water is almost as easily carri[illegible] out as above water. Oxygen machinery is also employed for cutting ste[illegible]

Fig. 5.

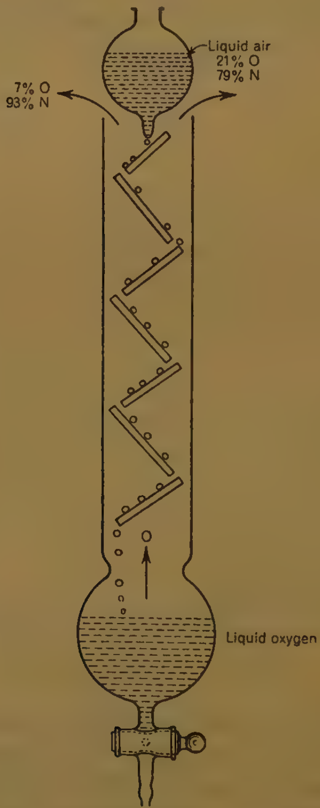


plate and forgings, and as a result a comparatively large industry ha[illegible] grown up in the manufacture of fabricated structures.

In recent times metal-spraying has come into considerable use by mean[illegible] of a special pistol which is fed with oxygen, fuel-gas, and compressed air[illegible] Any ductile metal can be sprayed on to wood, fabric, and many othe[illegible] materials.

In the liquid form, oxygen absorbed by charcoal in paper cartridge[illegible] forms an explosive mixture suitable for use in mines where firedam[illegible]

absent. The medical use of oxygen is most extensive. Indeed, oxygen pparatus is an essential part of the equipment of all modern hospitals.

In the separation of nitrogen by modern rectifying processes, a purity 99·8 per cent. can be obtained. To-day single plants are in operation hich produce as much as 80 tons of nitrogen per day. The nitrogen is sed in the manufacture of cyanamide, a nitrogenous fertilizer formed by assing nitrogen gas over heated calcium carbide, and it is also used for e manufacture of synthetic ammonia.

Argon, which was discovered by Rayleigh and Ramsay in 1894, exists the air to the extent of only about 1 per cent. It may appear to be of egligible importance, yet its extraction and use are saving us many illions of pounds every year in our electric-light bills. Indeed, for the ectric-lamp industry alone, over 10 million cubic feet of argon are eparated from the air every year, and because of its use we get nearly wice as much light for our money as we did previously. When the ungsten filament replaced the carbon filament in the electric lamp, the fficiency was greater because of the higher temperature at which it could e run. If the temperature were raised too high, evaporation of the etal produced blackening of the bulb and resulted in a shorter life for he lamp. In 1912 it occurred to Langmuir that the evaporation could e reduced by putting the metal under gaseous pressure by the introduction f a chemically-inert gas. In the first gas-filled lamps nitrogen was used, ut argon is more efficient, for not only is it chemically inert, but its power f carrying off heat from the filament is less than that of nitrogen. At he present time more than 1,000 million lamps containing argon are nade every year, and it has been estimated that the annual saving in ur lighting bill is many millions of pounds. This result could not have een obtained without refrigerating machinery.

Neon is another gas in the atmosphere and it also is extracted by low-emperature separation. Neon is largely used in electric vapour-discharge ubes for advertising purposes, and it has the low boiling-point of 27·2° K.

Hydrogen from Water-Gas and Coke-Oven Gas.

Air is the most plentiful mixture of gases we have, and hence the method of separation by compression, expansion, and rectification was first applied to it. There are, however, other gas-mixtures to which the method has been applied. Important examples are water-gas and coke-oven gas. Water-gas consists mainly of a mixture of hydrogen and carbon monoxide. The latter has the higher boiling point, and most of it is separated by liquefaction, leaving the hydrogen in a gaseous form. Traces of impurities are removed by passing the residual gas through a separating vessel surrounded by liquid nitrogen. Nearly pure hydrogen is thus obtained.

Coke-oven gas, after being freed from ammonia, benzol, and sulph
has an average composition as follows :—

Hydrogen	50 per cent.
Methane	22 ,,
Carbon monoxide	6 ,,
Carbon dioxide	3 ,,
Oxygen	1 ,,
Nitrogen	16 ,,
Other gases	2 ,,

After compression the carbon dioxide is removed by washing wi high-pressure water and caustic soda. Various constituents of the g are then separated by successive liquefactions, and hydrogen remai Ordinary coal-gas, the composition of which is not very different fr coke-oven gas, may be treated similarly. The hydrogen is used for t manufacture of ammonia, the nitrogen for which is obtained by liqu faction of the air. The Claude method is also used for separati hydrogen from coke-oven gas.

Solid Carbon Dioxide.

The critical temperature of carbon dioxide is 304° K., or 31° (so that at ordinary temperatures carbon dioxide can be liquefied b increasing the pressure. Work is done on the molecules of carbon dioxi by pressing them closer together, and as a result their kinetic energy increased; that is, the temperature is raised. By cold water or oth means the temperature is restored to normal, and when the pressure sufficiently great the mutual attraction between the molecules produc liquefaction. In practice, the temperature is kept below 20° C., and th pressure used is about 80 atmospheres.

There are several methods for producing solid CO_2. In one the vapou over the liquid is allowed to expand, with the result that some solid in th form of " snow " is produced, the gaseous CO_2 being drawn off and r compressed. When the vessel is nearly full of " snow " it is flooded wit liquid CO_2 to form a slush. Evaporation at atmospheric pressure allowed to take place, and the contents of the vessel freeze to a soli block.

As solid CO_2 passes from the solid to the gaseous state without passin through the liquid condition at ordinary temperatures and pressure it is impossible to have liquid CO_2 in ordinary industrial practic and this makes the handling of solid CO_2 an easy matter. There is n drip.

The demand for solid CO_2 in Great Britain is increasing rapidly. I is used for the preservation of food and to an ever-increasing extent f

e storage and transport of ice-cream. In the United States the mand for solid CO_2 is about 50 million lb. per annum.

Modern Low-Temperature Research.

The expansion of a compressed gas with or without external work ing done, coupled with the cooling due to evaporation of the resulting uid, has been used to obtain temperatures less than 1° K. Whilst is most improbable that the absolute zero of temperature can ever be ached, advantage has been taken of the magnetic properties of matter approach it very closely.

The phenomena we know as magnetism are due to the existence of omic magnetic dipoles. When these are placed in a magnetic field, the ementary magnets are pulled in the direction of the field. The motion the atoms which constitutes temperature resists this, and so the resulnt magnetic field depends on the temperature as well as the intensity the magnetic field. The higher the temperature, the less the magnetizaon. In general, the magnetic dipoles get arranged in orderly fashion at mparatively high temperatures, but there are a few substances, such as on ammonium alum, in which random orientation exists at very low mperatures. When these substances are at the lowest temperature tainable by the methods previously described, and a magnetic field is eated, the field controls the dipole directions and heat is developed. his heat is slowly absorbed by the cold surrounding substances, and hen the low temperature has been restored the magnetic field is removed. he dipoles get back to some extent into the disordered condition again, nd consequently the temperature drops. In this way a temperature as w as 0·003° K. has been attained.

It is of interest to note that the electrical resistance of pure metals has een found to be proportional to their absolute temperatures, except hen very near the absolute zero of temperature. With some metals, at temperature a few degrees above the absolute zero, the electrical resistnce disappears—a condition known as "supra-conductivity." It has rther been discovered that the presence of a magnetic field lowers the emperatures at which this supra-conducting state occurs. Niobium rbide is supra-conducting at as high a temperature as 12° K. No oubt the electrical engineer is hoping that some day research will find aterials which are supra-conducting at moderate temperatures; maybe uch a discovery would enable midget transformers to be built for the ransformation of vast quantities of electrical energy.

Latent Heat of Evaporation.

As already stated, in the case of a liquid the molecules are regarded as eing in touch with one another as well as being in a state of motion.

The majority of the molecules, which approach the surface more or le[ss] vertically from the interior of the liquid, have their motion checked [by] the attractive force of the other molecules, and are forced to turn bac[k]. But many molecules, which approach the surface with an exceptiona[lly] high velocity, overcome this attraction and pass into the upper gas-spac[e]. In doing so, work is done against the attractive force of the molecu[les] and the kinetic energy is correspondingly reduced. Any gas molecul[es] which come near the liquid surface from above are attracted by t[he] molecules at the surface and are drawn into the liquid. There is equi[li]brium when as many molecules leave the surface as enter it. The numb[er] of molecules with sufficiently great velocities to leave the surface may [be] estimated from Maxwell's distribution-law. *Fig. 1* (p. 244) shows how t[he] distribution varies with temperature, the number of molecules with reall[y] high velocities increasing appreciably with rise of temperature. This e[x]plains the rapid increase of vapour-pressure.

As the more rapidly-moving molecules are the ones which leave t[he] surface, it follows that the average intensity of the translatory moti[on] inside the liquid is reduced: that is, the temperature is lowered. If t[he] re-entrance of rapidly-moving molecules is prevented by pumping off t[he] vapour as soon as formed, and at the same time precautions are taken [to] prevent heat from entering the liquid from the outside, very low temper[a]tures may be obtained. Water may easily be frozen in this way and wi[th] ether a reduction of temperature of 130° C. may be obtained.

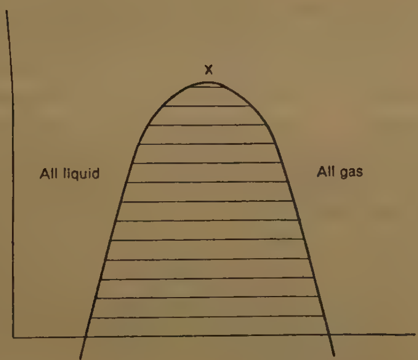
The latent heat of evaporation of a liquid may be great or sma[ll] according to the distance apart of the molecules of the vapour or gas, an[d] obviously this distance may be controlled by pressure. The work done [in] tearing a molecule from its near neighbour in a liquid to join other simil[ar] molecules in a gaseous condition is represented by a part or the whole of th[e] shaded area of the curve C in *Fig. 2* (p. 245). The whole of the shaded are[a] would represent the work done if the gaseous molecules were so far apa[rt] that the attractive forces between them were negligible. For molecul[es] nearer together the work done will be less, and since increase of pressu[re] diminishes the molecular distance, the work done in separating the molecul[es] diminishes with increase of pressure. An increase of pressure may b[e] represented by an advance of the ordinate DE towards O. As DE nea[rs] O the amount of work represented by the shaded area ODEC gets small[er] and smaller, and vanishes when D coincides with O. The results of suc[h] an imaginary experiment, if plotted, might be shown in a diagram such a[s] *Fig. 6*, where horizontal distances in the shaded area are proportional t[o] the heats of evaporation. On the left of the area the substance would b[e] entirely liquid and on the right it would be entirely gaseous.

As previously stated, above a certain temperature, known as th[e] critical temperature, a gas cannot be liquefied however great the increas[e] of pressure. We can now picture why this is so. With increase o[f] temperature the pressure of a gas at constant volume is raised, and if thi[s]

essure is above that corresponding to X in *Fig. 6* the substance corre-onds to both liquid and gas, and there is no visible change of state how-er great any additional pressure may be. All gases show this behaviour, ıt the critical temperatures, pressures, and volumes differ widely.

Because of the transformation of external heat through the medium a liquid into kinetic energy of liquid molecules and kinetic and potential ergies of gaseous molecules, the steam-power engineer continually rives to get more and more kinetic energy into the steam and less and ss of those forms of energy which his engine is unable to convert into eful work. For this reason the temperature, and therefore the pressure, steam-generation has increased as well as the temperature of superheat. rominent among the types of high-pressure steam generators is the

Fig. 6.



enson boiler, in which the water is heated to a temperature beyond ıe critical temperature of 374° C. The pressure is about 3,200 lb. per quare inch. The water is then converted into steam without change f volume or addition of heat of vaporization. This subject of high-ressure steam-generation for land and marine purposes is of very great nportance for Great Britain, for such high-pressure generating-systems re more efficient thermally.

Evaporation and Refrigeration.

The apparently insignificant cooling-effect due to the evaporation of liquid—a phenomenon which has been known for thousands of years, lthough the mechanism was unknown until the nineteenth century—is, s I have said, the basis of most modern refrigerating machines. In the ase of many liquids the cooling effect at atmospheric pressure is small ut, as we have seen, a considerable reduction of temperature can be

17

obtained by pumping off the vapour formed above the surface. Indee about a century ago Faraday reached a temperature of 160° K., —113° C., by evaporating a liquid under an air-pump. The limits temperature which can be so attained with water, ether, oxygen, hydroge and helium are approximately as follows :—

Substance.	Boiling-point: °K.	Temperature attainable by evaporation: °K.
Water	373	230
Ether	308	170
Oxygen	90	55
Hydrogen	20	9
Helium	4	1

The present refrigeration-practice depends on the principle that so substances, which exist as vapours at ordinary temperatures and pressure may be liquefied upon being subjected to higher pressures, but witho lowering of temperature; that is, the ordinary temperature is well bel the critical temperature of the substance. It is necessary, therefore, th any pumping mechanism should not only exhaust the vapours from t upper surface of the liquid, but should also be able to compress the The two principal substances in use are ammonia and carbon dioxide, an it is part of the process to collect the vapours and to compress them the liquid state again, so that they move in a cycle. Imagine a start be made with gaseous ammonia. When compressed, the molecules a pushed together. Any heat produced is extracted by cold water, whi surrounds the container. The attractive force between the molecul becomes more and more effective, and eventually the ammonia liquefie This cold liquid refrigerant is forced through an expansion- or throttlin valve, and the pressure is reduced by suction to such an extent that t liquid boils in the cooling coil of the evaporator. Brine which is in t evaporator is thus cooled and is circulated through pipes and tanks may be desired. A diagram of such a refrigerating system is shown *Fig. 7.*

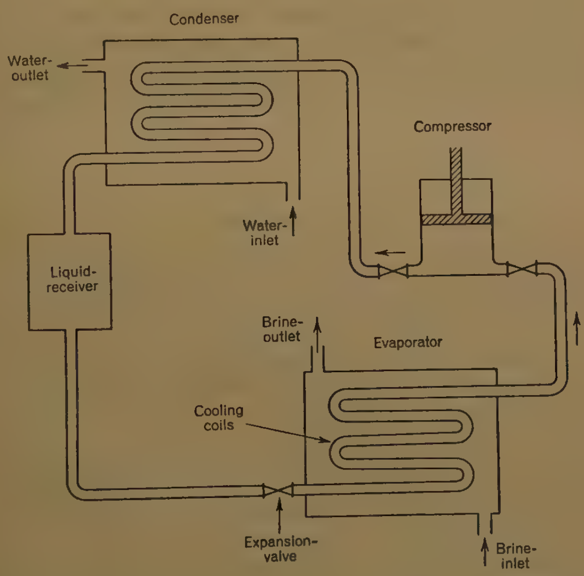
Uses of Cold Brine and Artificial Ice.

Cold brine is used directly or through the medium of ice on a mo extensive scale. It is impossible to describe its many uses here, includi as they do the cold storage of bulbs, which, incidentally, has revolutioniz the spring-flower markets; the freezing of breakfast-rolls in order th they may be kept "fresh" for the morning meal; the conditioning air for public rooms; cold depositories for furs, carpets, blankets a many textile goods; the chilling of milk, peas, beans, spinach, a broccoli; the formation of ice in skating-rinks; the freezing of groun

y the civil engineer for shaft-sinking and tunnelling in waterlogged rata; and above all, its extensive use in the transport and storage of all nds of food.

It is of interest to note that the first artificial ice-rink was constructed Chelsea in 1876, and that the first successful application of refrigeration borings in water-laden strata was by Siebe, Gorman and Company of ondon as long ago as 1862. In the sinking of wells in mining and in nnel-building, a water-bearing stratum gives the engineer more trouble han anything else. In very difficult cases refrigeration of a portion of he water-saturated area renders easy an otherwise difficult or impossible

Fig. 7.



ask. The freezing process consists in the formation of a solid wall of ice round the ground to be excavated. The ice wall is formed by drilling a umber of holes in which freezing-pipes are inserted and through which old brine is circulated. Cylinders of hard frozen earth are formed around ach brine-pipe, and the freezing is continued until these cylinders join ogether and a hard cylindrical core is obtained. This can then be xcavated in a normal manner.

The use of brine-systems of refrigeration for the transport of food verseas is of vast importance. Whereas 60 years ago there was no efrigerating machine and no cold storage provided in ships, to-day the efrigerated space in ships bringing food to Great Britain alone amounts o not less than 100 million cubic feet, equivalent to a cold store as wide

as Victoria street, 20 feet high and 13 miles long. To-day there are sing ships having refrigerated spaces of over 500,000 cubic feet capacity, an capable of carrying cargoes of 5,000 tons of chilled or frozen meat. Th number of vessels holding refrigerating certificates has risen from o hundred and seventy-four in 1915 to five hundred and forty-six in 193 The capacity of the public cold stores in Great Britain amounts to abo 50 million cubic feet, whilst our annual output of artificial ice is the order of 1,250,000 tons, of which the fishing industry uses 750,0 tons.

The imports of chilled and frozen meat into Great Britain in 19 totalled 19 million cwt. and were valued at £39,000,000, whilst the tot value of the refrigerated food-produce imported was over £110,000,0 No fewer than thirty countries contribute to our food-supply by the he of refrigeration, and it may truly be said that the food which we eat now practically independent of the seasons. The industry of mode refrigeration is indeed an outstanding feature of the world's econom progress.

Conclusion.

I feel that the task I set myself is far from complete. At the outs I was informed that the general idea of the James Forrest Lectures w to indicate the bearing of the advances in abstract science on the art an science of engineering. I therefore chose as my main objective the wa in which the modern industry of refrigerating engineering is based knowledge of molecular motions, and particularly on the forces of attra tion and repulsion between molecules; as a secondary objective I hop to stimulate the interest of engineers in very low-temperature problem Such problems are being investigated at the Clarendon Laborator Oxford, and at the Cavendish Laboratory, Cambridge. In the prepar tion of this Lecture I have been particularly interested in the lo temperature work at Oxford, and I wish to thank Professor Lindeman for valuable information.

I have pointed out that in the preservation of food during transpo the use of refrigeration is increasing at a satisfactory rate. It is equal gratifying to state that in London alone there are in use over forty thousan of one type of domestic refrigerator. In very low-temperature wor however, progress is not so rapid. By refrigeration large quantities methane and hydrogen are available to engineers in Great Britain, an oxygen, nitrogen, and argon may be obtained in almost unlimited qua tities from the air. It is for the chemist and the engineer to consider ho these gases could be best employed. Their separation by means refrigeration is not an expensive process. On the contrary, it is com paratively cheap.

Sir Clement Hindley, Vice-President, in moving a vote of thanks to e Lecturer, said he regarded it as a great privilege to be asked to do so. ie Institution owed a double debt of gratitude to Sir Frank Smith for livering his Lecture that evening, for, though probably most of those esent were unaware of the fact, a few hours previously Sir Frank had en in attendance on His Majesty the King at the opening of the Glasgow mpire Exhibition. Sir Frank had taken special measures to ensure that would be able to keep his two appointments; Sir Clement would not scribe him as a "disorderly molecule," but he had been doing that ternoon some of the things which he had said that molecules were doing the lecture theatre, having flown to London at over a hundred miles an our. He looked remarkably well on it, however, and it appeared to ve stimulated his efforts that evening.

The members were especially grateful to Sir Frank because he had, ith great frankness, exposed to them the workings of what might almost described as a unique mind. He had that rare combination of qualities, mind that could appreciate and explore fundamental scientific facts id an ability to bring them rapidly to the surface of practical application, as to enable ordinary engineers who were dealing with practical problems understand them. Conversely, he could very simply and easily analyse ie great facts with which engineers had to deal and translate them into indamental science, so that their essential basis became clear. He had egun his Lecture by describing the most profound and fundamental facts ith regard to atoms and molecules, and had brought his audience steadily hrough the Lecture until they again faced the facts of their daily life— ie "Stop Me and Buy One" ice-cream man, and the high standard of ving which was now enjoyed, mainly through refrigeration. The embers also had to thank Sir Frank because for an hour he had taken iem away from their daily toil into the realms of scientific interest, and o one could go away from the Lecture without having his enthusiasm for ure science and its applications aroused and stimulated. He thought iat they ought to give him their most hearty thanks for the way in which e had entertained them and expounded to them the mysteries with which e had dealt.

Professor C. E. Inglis remarked that it was a great pleasure to ave the opportunity of seconding the vote of thanks to Sir Frank Smith, nd thus to pay his own humble tribute to the masterly Lecture which ir Frank had given. The subject, "Disorderly Molecules," was par- icularly fascinating, and Sir Frank had dealt with that disorderly subject n a most orderly manner; speaking as one who was fated in the course f the year to deliver a large number of lectures, Professor Inglis's admira- ion for the clarity of Sir Frank's Lecture was unbounded. He might dd that his admiration was most sincere as it was tempered with a certain mount of envy! Sir Clement Hindley had mentioned that Sir Frank, n addition to being omniscient, was also ubiquitous, and had very nearly

achieved the feat of being in two places at the same time ! The membe owed him a debt of gratitude for that, but it was very small in comparis with the almost unbounded gratitude that they owed him for his master Lecture, which would take an honoured place among the many oth memorable James Forrest Lectures.

ORDINARY MEETING.

10 May, 1938.

SYDNEY BRYAN DONKIN, President, in the Chair.

The Council reported that they had recently transferred to the class of

Members.

hn Goldwell Ambrose, O.B.E., M.C.
hn Aiton Bell.
arles William Knight.
bert Edward Leek.
aac Levin, B.Eng. (*Liverpool*), B.Sc. (Eng.) (*Lond.*).
William Rowand McKim.
Charles Bernard Mathews, M.B.E.
Eustace Savage Perrin, B.Sc. (Eng.) (*Lond.*).
Frank Walter Shilstone.

nd had admitted as

Students.

ancis Scott Marshall Adams.
eorge Colin Ash.
ewellyn Davies Baker.
athiaparanam Carthigesan.
ichard John Chamberlain.
hn Constable.
ichael James Corran.
ugh Lindsay Corry.
eorge Brammer Coutts.
onald John Primrose Cowan, B.Sc. (*Glas.*).
hn George Creet.
irk Wouter de Vos, B.Sc. (*Witwatersrand*).
eorge Ian Donaldson.
avin John Drummond.
aul Armand du Plessis.
illiam Lees Foster, B.Sc. (*St. Andrews*).
illiam Francis Fry.
hambiah Guneratnam.
harles Edgar Hallett, B.Sc. (Eng.) (*Lond.*).
enneth Vincent Walter Harding.
ernon Theodore Hill.
onald Rostron Hindley.
ekaripuram Ramaswamy Krishnaswamy Iyer.
onald Stanley Perera Jayasuriya.
rederick George Johnson.
Glyn Ingman Jones.
John Lloyd Jones.
Joseph Kennell.
Charles Ballantyne Kidd.
John Dryburgh Lindsay.
John McAra.
Keith McDonald.
Thomas West Macdonald, B.E. (*Sydney*).
Donald William MacLean.
Uttamlal Hemchandbhai Mehta.
Ian Malcolm Keith Miller.
James Morrison.
William Herbert Archibald Place.
Gerald Frederick Walter Plantema, B.Sc. (*Cape Town*).
Sidney Ernest Prentice, B.Sc. (*Cape Town*).
George Howard Pullin, B.Sc. (*S. Africa*).
Douglas Harry Ridout.
Charles George Hanson Rodgers, B.A. (*Cantab.*).
Kenneth Albert Rose.
Frank Herbert Russell.
Haribhai Bhagwanbhai Sidhpura, B.E. (*Bombay*).
Sanmugam Somasundaram.
Oliver Charles Stanford-Smith.
Amar Nath Sur.

John Mayne Swete, B.Sc. (*Bristol*).
Nilkanth Ramchandra Tembe, B.E. (*Bombay*).
William Ewart Thomas.
Frank Tilbrook, B.Eng. (*Sheffield*).
Charles Rasaratnam Tissainayagam.
James Elliot Turnbull.
Frank Thomas Bernard Wadswort[h]
Reginald Wallace, B.Sc. Tech. (*Ma[n]chester*).
Brian Kenneth Warner.
James Allan Watts, B.Eng. (*Liverpo[ol]*).
Eric Aubrey West.

The Scrutineers reported that the following had been duly elected a[s]

Members.

John Henry Bacon Forster.
Sydney Ernest Platt, O.B.E., B.Sc. (*Manchester*).
George Raw, B.Sc. (*Durham*).

Associate Members.

William Auld, B.Eng. (*Sheffield*).
Thomas Cecil Hartley Bateson, Stud. Inst. C.E.
Robert Lionel George Baxter, B.Sc. (Eng.) (*Lond.*), Stud. Inst. C.E.
Neville Borg, Stud. Inst. C.E.
Henry Richard Boyce, B.Sc. (Eng.) (*Lond.*), Stud. Inst. C.E.
Bernard Gerard Carroll, Stud. Inst. C.E.
Ronald Stephenson Cogdon, Stud. Inst. C.E.
Guy Musgrave Collins, B.Sc. (Eng.) (*Lond.*), Stud. Inst. C.E.
Edward James Edwards, B.Sc. (Eng.) (*Lond.*), Stud. Inst. C.E.
Reginald Cecil Gibson, Stud. Inst. C.E.
Harold Claude Harvey, B.Sc. (*Wales*), Stud. Inst. C.E.
Charles Ivan Haxell, Stud. Inst. C.E.
George Frederick Leadbeter, B.A. (*Cantab.*), Stud. Inst. C.E.
Brien Leonard Loffell, B.Sc. (*Witwatersrand*), Stud. Inst. C.E.
Geoffrey Alistair Lord, B.Sc. (*Ma[n]chester*), Stud. Inst. C.E.
Thomas Malcolm, B.Sc. (*Glas.*), Stu[d]. Inst. C.E.
Albert Gordon Osborne, Stud. In[st]. C.E.
Alexander Matheson Robertso[n], Stud. Inst. C.E.
John Ronald Sainsbury, Stud. In[st]. C.E.
Arthur James Watson Stonebrid[ge], Stud. Inst. C.E.
Venkatarama Subramaniam, B.[E.] (*Madras*).
James Richard Edward Taylor, Stu[d]. Inst. C.E.
John Kenneth Urwin, Stud. Inst. C.[E.]
Shanti Swarup Varma, Stud. Inst. C.[E.]
Erman Maneck Hayward Wadia, B.S[c]. (Eng.) (*Lond.*), Stud. Inst. C.E.
Andrew Welch, Stud. Inst. C.E.
James Norman Wilson, B.Sc. (En[g].) (*Lond.*), Stud. Inst. C.E.

ANNUAL GENERAL MEETING.

10 May, 1938.

SYDNEY BRYAN DONKIN, President,
in the Chair.

The Notice convening the Meeting was taken as read, as well as the inutes of the Annual General Meeting of 11 May, 1937, which were con-med and signed by the Chairman.

The following Report of the Council (pp. 270 *et seq.*) upon the Proceed-gs of The Institution during the Session 1937–1938 was read, the State-ent of Accounts (pp. 290–300) being taken as read.

The President moved—That the Report of the Council be received d approved and that it be printed in the Journal of The Institution.

Mr. W. J. E. Binnie, Vice-President, seconded the motion.

Mr. I. C. Barling, in discussing the motion, said that he had been a orporate Member for nearly 50 years, and had retired from active practice r nearly 20 years; thus he was able in a way to view The Institution from e outside. The qualification of The Institution did not appear to be ceived with the same general respect to-day as it used to be 50, 20, or even years ago. He thought it would be agreed that The Institution had less fluence with the public than it used to have, and he suggested that there ight be one or two matters for consideration in that connexion.

In the first place, with regard to the admission of Students, a *viva voce* xamination, or at any rate a personal interview with each candidate, ight well be instituted. It was possible to tell more by talking to a man r 3 minutes than by all the examinations in the world. He would suggest hat The Institution had made scholarship a fetish, and that a little more ttention should be paid to what might be called personality. It was ssential that those entering The Institution should be men of personality nd of high character. Arising out of that, there was another small hatter. In a number of bodies similar to The Institution, where a man had een so unfortunate as to reach the age of, say, 35, never having obtained is School Leaving Certificate, there was some method of allowing him to e exempted from examination after such an interview. He had a articular case in mind of a most desirable man who, through having had o leave school early, had not taken his School Certificate. That man was ow about 35 years of age, and had not reached such a position of eminence s would permit him to become a full Member without any examination; e was willing to take the professional examination, but was naturally rusty n his Latin and Greek. Mr. Barling would like to suggest, therefore, that

there should be some method of accepting really desirable candida without their having to go back to their schoolmasters in circumstances that kind.

His second point was that the conduct of members should be watch very carefully. The Institution had, he knew, a disciplinary committ which was supposed to deal with any breaches of professional etiquet Unfortunately, however, that committee appeared to do little more th administer a mild reprimand. It ought to be able to say, "This man h injured someone, and he must make suitable reparation." That mig have been done on occasions, but he had not heard of it.

The third subject on which he wished to touch was that of the method election of the Council. There was some possibility of effective voti for the election of ordinary Members of Council, but there was really method of election at all in regard either to the President or to the Vic Presidents. It could not be conceived that anyone could possibly secu sufficient votes for a special candidate in preference to one of the nam already on the list. He suggested, therefore, that the names of the tw senior Vice-Presidents should be put forward for election to the office President, and that an extra name should be added to the number requir for the Vice-Presidents.

Mr. A. T. Best suggested that the discussions at the Ordinary Meetin and the Informal Meetings might with advantage take the form of deba rather more than they did. In recent years the practice had developed members taking part in the discussion on a Paper being permitted read from their notes, so that what the Meeting really heard was the readi of the Abstract of the Paper, followed by a succession of minor essays the same subject. He suggested that it might be better if members we allowed to speak from their places in the lecture-theatre, and if th reading from notes—although notes were often necessary for reference were discouraged. The deliberate reading *in extenso* from notes should, I thought, be disallowed. The same remarks applied even to the Inform Meetings, which used to be held in the reading-room; he admitted th advantages of holding them in the lecture-theatre, but the old freedo had been lost. With the exception that the Informal Meetings we not reported in full and that members were permitted to smoke, the differed very little from the Ordinary Meetings; the increased formaliti of the Informal Meetings was, he thought, a great loss. He was we aware that the matter he had raised was one which rested more with th members than with the Council, but, so far as it did rest with the Counci he would ask them to do what they could to bring about a freer method debate.

Mr. H. C. Lloyd, referring to the matters raised by Mr. Best, expresse the view that it was certainly desirable that the Discussions should be dis cussions, and not mere readings from notes. He did not feel at all dis posed, however, to support any suggestion that members should spea

m where they stood, because to anyone whose hearing was not very ute it was exceedingly difficult to hear members unless they were placed ar the microphone. He would also say that some members, even when ey were placed near the microphone, were very reluctant to let their ices reach it, and he would suggest that in future they should be asked speak into it.

Sir John Thornycroft suggested that if a return were made to less mal conditions, people who spoke from the body of the hall without sing their voices sufficiently to make themselves heard would not be tened to, and that would teach them to speak up!

Mr. J. A. Baird said he was not altogether in agreement with Mr. rling's remarks, as engineering was now a science and examinations re therefore necessary.

The President said that if there were no further points which Members shed to raise he would put the resolution to the Meeting, but before ing so he would like to state that the Council would most willingly con-ler the points which had been raised by the various speakers, as they had ways done in the past.

The Meeting then resolved—That the Report of the Council be received d approved, and that it be printed in the Journal of The Institution.

The Scrutineers reported the election of the Council for 1938–1939 as llows:—[1]

President.

WILLIAM JAMES EAMES BINNIE, M.A.

Vice-Presidents.

r Clement Daniel Maggs Hindley, K.C.I.E., M.A.
aurice FitzGerald Wilson.
Sir Leopold Halliday Savile, K.C.B.
Professor Charles Edward Inglis, O.B.E., M.A., LL.D., F.R.S.

Other Members of Council.

thol Lancelot Anderson, C.B.
avid Anderson, LL.D., B.Sc.
homas Henry Bailey.
eorge Ernest Bennett, M.Sc. (*India*).
isa Binns.
ohn Job Crew Bradfield, C.M.G., D.Sc., M.E. (*Australia*).
aymond Carpmael, O.B.E.
rederick Charles Cook, C.B., D.S.O., M.C.
Sir Harley Hugh Dalrymple-Hay.
Jonathan Roberts Davidson, C.M.G., M.Sc.
Charles George Du Cane, O.B.E., B.A.
Thomas Peirson Frank.
Ralph Freeman.
Griffith John Griffiths.
William Thomson Halcrow.
Charles George Hawes, B.Sc. (*India*).

[1] The Council commence their term of office on the first Tuesday in November, 938.

Roger Gaskell Hetherington, C.B., O.B.E., M.A.
Ralph Frederick Hindmarsh.
Drummond Holderness (*New Zealand*).
Alfred Dale Lewis, M.A. (*South Africa*).
William Henry Morgan, D.S.O.
Alexander Newlands, C.B.E.
Francis Ernest Wentworth-Sheil O.B.E.
Julian Cleveland Smith, LL (*Canada*).
Reginald Edward Stradling, C. M.C., D.Sc., Ph.D.
Sir John Edward Thornycro K.B.E.

Mr. J. S. Wilson proposed—That the thanks of The Institution accorded to the Scrutineers, and that the ballot-papers be destroyed.] mentioned that for many years many of the members had felt that filling up the ballot-paper they had not had very much power in t choice of the Council. In the ordinary way, if it were thought that, example, " Mr. Smith " should be on the council, his name was put the right-hand side of the paper and a certain number of names we crossed out to make the ballot-paper valid, so that votes would be ca for other people as well as for " Mr. Smith." Some people contrived give more value to their vote for " Mr. Smith " by adopting the expedie of putting down his name, crossing out all the others, and then, in ord to make the ballot-paper valid, writing in names from the List of Membe starting " Aaron," " Abraham," " Absalom " and so on.

Mr. H. G. Lloyd seconded the resolution, which was carri unanimously.

Mr. J. D. C. Couper, on behalf of the Scrutineers, expressed the thanks for the resolution that had been passed, and remarked that if t system of voting described by Mr. Wilson became usual the task of t Scrutineers might become such that it would be impossible to comple the scrutiny in time for the Annual General Meeting. He mention the effect of the change made by the Council in the order in which ne candidates appeared upon the ballot-list. When they had appeared alphabetical order, there had been evidence of a definite " alphabeti complex " among voters, by which those whose names appeared earlier the alphabet obviously had some benefit. The new arrangement, so f as could be judged by 2 years' experience, seemed to show that membe were generally voting for candidates on their merits rather than on t order in which they appeared in the list, which was all to the good. Son voters seemed to find it difficult to adhere to the very simple rules; f instance, quite a number could not erase four names in accordance with t directions on the ballot-papers, but instead placed a cross opposite eve name except four. Finally, he would like to refer to the fact that elev papers had been received in envelopes bearing only a halfpenny stam the flaps having been tucked in but not secured with gum. That practi raised a difficult problem, because the question to be determined w

ether or not those ballot-papers were valid. The rules specified that the pers had to be posted in a closed envelope, and it was not clear whether envelope with the flap turned in but not secured with gum could be nsidered to be closed. The conclusion had been reached that, to prevent y possibility of ballot-papers being tampered with, it was advisable that mbers should make use of the gum provided.

Mr. A. W. E. Bullmore proposed—That the thanks of The Institution given to Mr. E. W. Monkhouse, Honorary Auditor, and that he be ppointed Honorary Auditor for the current financial year, and that Sir an Rae Smith be appointed Professional Auditor in the place of the late . P. D. Griffiths.

He observed that the Members owed a very great debt of gratitude to . Monkhouse for all the work he had put in over a number of years, and at they very much regretted the passing of Mr. Griffiths.

Mr. H. W. S. Husbands seconded the resolution, which was carried animously.

Mr. W. T. Halcrow proposed—That the thanks of this Meeting be corded to Mr. Sydney Bryan Donkin, President, for his conduct of the siness as Chairman of the Meeting. He remarked that it was unneces- ry for him to say anything in support of the motion, as all those present ew that their President was always an excellent chairman.

Mr. J. D. C. Couper seconded the resolution, which was carried by clamation.

The President thanked Mr. Halcrow, Mr. Couper, and all those who d supported the resolution. It had been a pleasure to him to be present at evening and to conduct the meeting, as indeed it had been a pleasure him to preside at the Ordinary Meetings whenever he had been able to so.

The proceedings then ended.

REPORT OF THE COUNCIL, 1937–38.

Before presenting, in accordance with the By-laws, their report up the state of The Institution, the Council wish to record their sense the great loss to The Institution occasioned by the death on the 29 June, 1937, of Dr. Henry Homan Jeffcott, B.A., B.A.I., M. Inst. C. for over 15 years Secretary of The Institution, whose valued servi have been much appreciated and whose geniality and charm of mann won for him the warm esteem of all with whom he came in contact the course of his work.

On the 18th December, 1937, the Council appointed Mr. E. Graha Clark, M.C., B.Sc., M. Inst. C.E., as his successor.

The Council have to state that they have continued to seek clo co-operation with other engineering societies in the firm conviction th The Institution, being competent under its Charter to promote t advancement of engineering science in all its branches, is in a positi to assist collaboration between the specialist societies and to prom co-ordination among all professional engineers. They wish to expr their appreciation of the response they have received, and wou refer in particular to the opinions expressed in this connexion by George Lee, O.B.E., M.C., in his Presidential Address to the Institutio of Electrical Engineers last October. The results achieved in this rega during the session under review are briefly summarized below.

Joint Meetings.—In the belief that there are no definite bounda lines between the various branches of engineering and that The Instituti may be regarded as a common meeting ground where subjects coveri more than one of these branches may be discussed, joint meetings ha been held with the Institution of Electrical Engineers, the Institution Chemical Engineers, and the Institution of Structural Engineers. addition, a joint meeting with the Institution of Automobile Enginee and fifteen other bodies was held in the Great Hall of the Institution, wh a symposium of Papers on "The Essential Road Conditions governi the Safety of Modern Traffic" was presented. The interest displayed these meetings has amply confirmed the view held by the Council in th respect.

Engineering Education.—The Council welcome the steps taken the Engineering Joint Council to introduce a common prelimina examination, and they propose to co-operate in the fullest sense in th

deavour to avoid the duplication of examinations. The Council have ently approved regulations by which corporate members of certain gineering societies who have passed the professional examinations of ose specialist institutions will be accorded exemption from the equivalent rts of the Associate Membership Examination of The Institution. ore detailed reference to this is made later in this Report.

Research.—The possibilities of active co-operation with other stitutions and bodies in the field of engineering research have also ceived close consideration, as a result of which negotiations with a number bodies have taken place. *Ad hoc* co-operation has been arranged tween certain Institutions in individual cases of research of common terest by the formation of a joint committee in control of such research th joint financial support. In the case of the Institution of Mechanical ngineers, close contact is being maintained by an annual joint review the two research committees of the programmes of research.

Engineering Abstracts.—In a similar way the Council have found possible to co-operate with nine engineering Institutions, and with the epartment of Scientific and Industrial Research and the Safety in Mines esearch Board, in the issue of "Engineering Abstracts" in the new form hich was introduced in January, 1938. The possibility of further -operation with engineering bodies both in Great Britain and overseas now under investigation. Details of the changes are given later.

Overseas Associations.—Proposals for securing co-operation between embers of British engineering institutions resident overseas are at present ceiving the consideration of the constituent Institutions of the Engineer-g Joint Council, and the Council of The Institution have agreed to explore e proposals with a view to ascertaining whether they would be generally ceptable.

Public Relations.—The work of the Engineering Public Relations ommittee, consisting of representatives of fourteen leading engineering cieties, and with Sir Clement Hindley, K.C.I.E., M.A., as Chairman, hich was appointed as a result of a joint meeting held at the Institution n the 16th December, 1936, has been the subject of a report of the Com-ittee for the year ending 31st March, 1938. It will be sufficient here say that a programme of work is being carried out which should fectively assist the object for which the Committee was created, namely, present to the public in suitable form information concerning the ience and practice of engineering and its services to the public.

Ordinary Meetings.—The opening meeting of the session was held n the 2nd November, 1937, when Mr. S. B. Donkin delivered his residential Address, in which he briefly reviewed the progress in the eneration and application of electricity during the last 30 years. He ompared the cost of generation by steam, internal-combustion engine, nd water-power, and referred to the question of distribution and to he value of electricity as a commodity.

Fifteen Ordinary Meetings have been held, at which the Pa
mentioned below were discussed, and one Lecture delivered :—

SUBJECT.	AUTHOR.
Combustion-Efficiencies of Gas and Oil Engines.	W. A. Tookey, M. Inst. C.E.
Dover Train-Ferry Dock.	George Ellson, O.B.E., M. Inst. C
The Design and Operation of the Coleshill Sewage-Disposal Works of the Birmingham Tame and Rea District Drainage Board.	F. C. Vokes, B.Sc. (Eng.), Assoc. Inst. C.E.
The Reconstruction of Chelsea Bridge.	E. J. Buckton, B.Sc. (Eng.), a H. J. Fereday, MM. Inst. C.E.
Recent Engineering Developments in the General Post Office.	Sir George Lee, O.B.E., M.C.
The Subsidence of a Rockfill Dam and the Remedial Measures Employed at Eildon Reservoir, Australia.	R. G. Knight, M.C., M.C.E., M. In C.E.
An Experimental Investigation of the Effect of Bridge-Piers and Other Obstructions on the Tidal Levels in an Estuary.	Professor A. H. Gibson, D.Sc., LL. M. Inst. C.E.
The Deformation and Fracture of Metals.	H. J. Gough, M.B.E., D.Sc., F.R and W. A. Wood, M.Sc.
The Galloway Hydro-Electric Development, with Special Reference to the Constructional Works.	William Hudson, B.Sc. (Eng.), a J. K. Hunter, B.Sc. (Eng.), M Inst. C.E.
The Galloway Hydro-Electric Development, with Special Reference to the Mechanical and Electrical Plant.	William Hawthorne, B.E., M. In C.E., and F. H. Williams, B. Tech., Assoc. M. Inst. C.E.
The Galloway Hydro-Electric Development, with Special Reference to its Inter-Connexion with the Grid.	R. W. Mountain, B.Sc. (Eng.), Inst. C.E.
Engineering Problems Associated with Clay, with Special Reference to Clay Slips.	T. H. Seaton, M. Inst. C.E.
Constructional Work of the Fulham Power-Station.	J. F. Hay, M. Inst. C.E.
Fulham Base-Load Power-Station: Mechanical and Electrical Considerations.	W. C. Parker, A.M.I.E.E., a Hubert Clarke, A.M.I.Mech.E.

(Joint Meeting with the Institution of Electrical Engineers.)

he Reconstruction of Main Road Bridges, Calcutta.	M. R. Atkins, C.B.E., B.Sc. (Eng.), and D. H. Remfry, B. Eng., MM. Inst. C.E.
he Work of the Paint Research Laboratory of the London Midland and Scottish Railway Company.	Frank Fancutt, F.I.C., A.M.I. Chem.E.
uthampton Docks Extension.	M. G. J. McHaffie, M. Inst. C.E.
cture :—Air Raids as They Affect the Work of the Civil Engineer.	Colonel William Garforth, D.S.O., M.C. (late Royal Engineers).

The awards for Papers read and discussed at Ordinary Meetings, for apers published with written discussion only, and for Students' Papers ill be announced in the October Journal.

Informal Meetings.—Six Informal Meetings were held, the subjects nd names of the Introducers being as follows :—

SUBJECT.	INTRODUCER.
The Education and Training of the Engineer to Meet Modern Requirements."	Professor J. F. Baker, M.A., D.Sc., Assoc. M. Inst. C.E.
Electrical Peak-Loads and Methods for dealing therewith, with Special Reference to Hydraulic Storage."	R. W. Mountain, B.Sc. (Eng.), M. Inst. C.E.
The Purchase and Use of Concrete in a Pre-Mixed Form."	R. H. H. Stanger, Assoc. M. Inst. C.E.
The Resistance to Fatigue Stresses of Welded and Riveted Joints."	Professor F. C. Lea, O.B.E., D.Sc. (Eng.), M. Inst. C.E.
Materials Available for, and Jointing of, Water Mains."	H. F. Cronin, M.C., B.Sc. (Eng.), M. Inst. C.E.
Sub-Surface Investigations by Electrical Methods."	H. M. Gell, M.C., M. Inst. C.E.

Lectures.—The Vernon-Harcourt Lecture on "Estuary Channels nd Embankments" was delivered before the Association of London tudents on the 8th December, 1937, by Dr. Brysson Cunningham, 3.E., M. Inst. C.E., and was repeated at meetings of Local Associations t Belfast, Birmingham, Bristol, Cardiff, Glasgow, Manchester, Newcastle, heffield and Southampton.

The forty-fourth James Forrest Lecture was delivered on the 3rd May y Sir Frank Smith, K.C.B., C.B.E., D.Sc., LL.D., F.R.S., Hon. M. nst. C.E., who took for his subject "Disorderly Molecules and Refrigerating Engineering."

Joint Meetings.—Three additional joint meetings were held wi other Institutions and engineering bodies as follows :—

18 January, with the Institution of Chemical Engineers, when a Paper " The Treatment and Disposal of Trade Waste Waters " was read Albert Parker, M.Sc., D.Sc., F.I.C.;

1 February, with the British Section, Société des Ingénieurs Civils France, and the Institution of Structural Engineers, when a Paper " Dunkirk Harbour Extension Works " was read by Monsieur L. Brice;

1 March, with sixteen other engineering bodies, when a symposium Papers arranged by the Institution of Automobile Engineers on " Th Essential Road Conditions governing the Safety of Modern Traffic was read and discussed :—

Section 1. " Road Planning," by Thomas Adams, D. Eng.;

Section 2. " Road Construction," by C. L. Howard Humphreys, T.D. M. Inst. C.E.;

Section 3. " Road Illumination," by L. J. Davies, M.A., B.Sc., an G. S. Lucas, M.I.E.E.

Students' Meetings and Visits.—The opening meeting of th Association of London Students was held on the 3rd November, whe Mr. Denis Temple, Stud. Inst. C.E., Chairman of the Association, ga an Address, in which he outlined the various forms of welding and the application to structural steelwork. Mr. S. B. Donkin, President Inst. C.E took the Chair. Five Papers have been read and discussed, an inform meeting was held, and a Lecture on " Long-Span Suspension-Bridges " w given by Professor C. E. Inglis, O.B.E., M.A., LL.D., F.R.S.

The fifty-seventh Annual Dinner of the Association of Lond Students was held at the Connaught Rooms on the 18th February, whe the President was the guest of the evening. Fifty-seven Students an guests were present.

Six Visits were paid to engineering works and good attendances we recorded—the largest being at the visit to the Dartford tunnel.

Local Associations.—The Council have approved the formation an Association of Corporate Members and Students having centres Portsmouth and Southampton. The Council wish this new Associati every success and trust that members and Students residing within th Portsmouth and Southampton districts will take full advantage of th facilities for the reading and discussion of Papers and for social intercour which this new Association offers.

The Council have also agreed to a considerable extension of th boundaries of the various Local Associations for the purpose of enablin the Honorary Secretaries to know how far to extend their solicitation to members who may wish to join an Association without encroachin on another Association's area.

The Council are particularly pleased to note the great increase in the mber of Papers by Students read before the Local Associations during e past session.

The Birmingham and District Association has 195 Corporate Members d 190 Students on its roll, as compared with 191 Corporate Members d 152 Students last year. Thirteen meetings have been held, including veral joint meetings with the local branches of other engineering societies d a joint meeting of Students, and four visits have taken place. The nual dinner was held on the 16th December, when there was an attendce of 133 members and guests.

The Bristol and District Association has held eleven meetings, nine Bristol and one each at Gloucester and Weston-super-Mare, and the nnual dinner was held at Bristol on the 27th January. The Association s on its roll 88 Corporate Members and 89 Students, compared with Corporate Members and 85 Students last session.

The Glasgow Association of Students has held nine meetings, including e at Edinburgh, and at two of these Papers were read by Students. ive visits to works have taken place, and the annual dinner, which was tended by 141 members and guests, was held on the 2nd February. The umber of Students attached to the Association is 205, an increase of 21 ver last year.

The Manchester and District Association has held twelve meetings, hile members of the Association have also attended, by invitation, eetings of the Liverpool Engineering Society and of the local branches f the Institutions of Mechanical, Electrical and Structural Engineers, nd three visits to works have taken place. The annual dinner was held n the 3rd February, when the attendance was 135. The roll of the ssociation numbers 152 Corporate Members and 153 Students, these gures being an increase of 21 Corporate Members and 25 Students on those r last year.

The Newcastle-upon-Tyne and District Association has 120 Corporate Members and 107 Students upon its roll, as compared with 120 Corporate Members and 66 Students last year. Seven ordinary meetings and seven tudents' meetings have been held at Newcastle and five meetings at tockton-on-Tees, and the Council are pleased to note that four Papers ave been contributed by Students. The annual dinner was held on the 9th January, and was attended by 121 Members, Students and guests, his number being a record for the Association.

The Northern Ireland Association suffered a severe loss during the ession by the death of its Chairman, Mr. C. F. Wheeler, B.A., B.E., M. Inst. C.E. Professor F. H. Hummel, M.Sc., Assoc. M. Inst. C.E., was ominated by the Committee as Chairman for the remainder of the session. The membership of the Association consists of 82 Corporate Members and 24 Students, a slight decrease on the numbers for last year. Ten meetings have been held, and the annual dinner was held at Belfast on

the 26th November, when 96 members and guests were present. Durin
the session a presentation was made to Mr. J. E. Harben, M. Eng., M. Ins
C.E., on his retirement from the honorary secretaryship, an office whic
he had held since the Association's inception in 1933.

The Portsmouth, Southampton and District Association was inaugurate
at a meeting held at Portsmouth on the 13th January, when Sir Leopo
Savile, K.C.B., Vice-President, and the Secretary Inst. C.E. were amon
those present, the former delivering a short address on "The Institutio
and its Local Associations." Four further meetings have been held, tw
at Portsmouth and two at Southampton, and a number of visits hav
been arranged for the summer. The Association has on its roll 10
Corporate Members and 48 Students.

The South Wales and Monmouthshire Association has 51 Corpora
Members and 54 Students upon its roll. During the session the Associatio
has held six meetings at Cardiff, including a joint meeting with the loc
branch of the Institution of Structural Engineers, two meetings at Swanse
and one at Newport, and a visit was paid to the Engineering Exhibitio
Cardiff. The annual dinner was held at Cardiff on the 15th December.

The roll of the Yorkshire Association numbers 159 Corporate Member
1 Associate and 114 Students, the latter figure being an increase of 29 c
last year. Eleven meetings have been held and four visits to engineerin
works were paid during the past year. The annual dinner was held a
Leeds on the 20th January, when 94 members and guests were presen
and when a presentation was made to Mr. James Urquhart, Assoc. M
Inst. C.E., former Honorary Secretary, in recognition of his services durin
a period of 7 years.

Overseas Associations.—The Buenos Aires Association has upon it
roll 94 Corporate Members and 17 Students, as compared with 9
Corporate Members and 17 Students for the previous year. During th
session seven meetings were held, at one of which three Papers by Student
were submitted for discussion, and three visits to works of engineerin
interest have taken place. The annual dinner of the Centre of Britis
Engineering and Transport Institutions, in which members of the Associa
tion joined, was held at Buenos Aires on the 13th May, in special com
memoration of the Coronation of Their Majesties King George VI an
Queen Elizabeth. On the 3rd December, a luncheon was given to M
J. H. Taylor, M. Inst. C.E., in recognition of the great interest he ha
taken in the affairs of the Association since its foundation 10 years ag
A further donation was received from Sir Follett Holt, K.B.E., M. Inst
C.E., to increase the fund bearing his name, and this will enable tw
awards to be made each year, one to a Corporate Member and one to
Student. The first award of the Follett Holt premium was made t
Mr. W. R. J. Murray, M. Inst. C.E., for his Paper on "Some Notes o
the Maintenance Work of the Buenos Aires Great Southern Railway."

The membership of the Malayan Association in October, 1937, wa

1 Corporate Members and 6 Students, as compared with a total member-ip of 112 for the previous year. During the session four meetings were eld and five visits were paid to engineering works and, as in previous ears, these have been held in conjunction with the Engineering Association Malaya. The annual dinner was held on the 9th October, 1937, when e attendance included the Governor, Sir Shenton Thomas, and Dr. avid Anderson, Member of Council. A premium to the value of $100 as awarded to Mr. F. Pelton, M.Sc., Assoc. M. Inst. C.E., for his Paper n "Model Tests on the Sungei Ijok Headworks."

The Shanghai Association has 27 Corporate Members on its roll. Dur-ng the past session twelve meetings have been held in conjunction with e local branches of the Institutions of Mechanical and Electrical Engineers nd the Engineering Society of China, at two of which Papers were read y members of the Association. Owing to the hostilities no visits were rranged during the session. A joint dinner of the local associations f the three Institutions was held, when the members were honoured by e presence of H.M. Ambassador to China.

Research.—The Report of the Research Committee covering their ork during 1935–6 and 1936–7 has recently been issued. Progress in e many investigations referred to therein has been continued during the ession.

An important programme of research into the Soil Corrosion of Metals nd Cement Products is under consideration, while the recommendations n respect of the design and construction of Reinforced-Concrete Structures or the Storage of Liquids, in respect of Breathing Apparatus for use in ewers, etc., and for regulations in respect of Earthing to Metal Water-Pipes and Mains are approaching completion. In connexion with the last mentioned a 3-year programme of research has been authorized. The research in Fish-Passes is nearly completed, while the researches on Special Cements for Large Dams, Wave-Pressures on Sea Structures, and Earth-Pressures have been extended for further periods.

During the year a Second Interim Report on Vibrated Concrete has been published.

Draft British Standard Specifications referred to The Institution for comment have continued to be examined by the Research Committee during the year.

Sea-Action Committee.—The Seventeenth (Interim) Report of the Committee on the Deterioration of Structures exposed to Sea-Action, describing the progress of investigations during the past year and giving the results of the 15-year tests on iron and steel specimens, is now in the press. The final examination of these specimens was carried out by Dr. J. Newton Friend, and a general report on the iron and steel experi-ments is now being prepared.

A certain number of timber specimens is still under exposure for the Committee in various parts of the world, and at Colombo a series of

creosoted specimens designed to show the effect of incision in securi better penetration of creosote has now been exposed for 3½ years. Repor on inspections of the above have been received, and in addition specime from Wellington have been sent to Professor George Barger, F.R.S., f examination during the year.

Tests on reinforced-concrete specimens exposed at the Buildi Research Station, Sheerness, and at the Gold Coast have continued.

Engineering Abstracts.—As from January, 1938, "Engineeri Abstracts" have been issued in sectionalized form, each section deali with one or with two or more allied branches of engineering, and bei limited to those branches for which abstracts are not already issued l specialist institutions and societies. Further, the Abstracts, which a issued monthly instead of two-monthly, contain references to importa articles appearing in journals published in Great Britain, instead of bei limited, as in the past, to abstracts from articles appearing in forei journals.

The sections of "Engineering Abstracts" now issued are :—

No. 1.—Engineering Construction.
No. 2.—Mechanical Engineering.
No. 3.—Shipbuilding and Marine Engineering.
No. 4.—Mining Engineering.

The Abstracts are issued in co-operation with the Institution of Nav Architects, the Institution of Municipal and County Engineers, th Institute of Marine Engineers (jointly responsible for the compilation Section No. 3), the Institution of Water Engineers, the Institution Engineers (Australia), the Midland Institute of Mining Engineers, th Midland Counties Institution of Engineers, the Mining Institute of Scotlan the North of England Institute of Mining and Mechanical Engineers, th Department of Scientific and Industrial Research, and the Safety in Min Research Board. This has made it possible for members of co-operatin bodies to obtain at special rates "Road Abstracts," compiled by th Department of Scientific and Industrial Research and the Ministry Transport and previously issued by the Institution of Municipal and Count Engineers; "Building Science Abstracts," compiled by the Buildin Research Station, Watford; and "Water Pollution Research-Summar of Current Literature," issued by the Water Pollution Research Board.

Nominations and Appointments.—Various nominations and appoin ments have been made or renewed by the Council during the past yea and The Institution is or has been represented on advisory or administrativ bodies and committees by the following members of The Institution :—

Royal Commission for Exhibition of 1851	The President.
Grant Committee of the Royal Society	The President.

eneral Board of National Physical Laboratory	Sir Alexander Gibb, G.B.E., C.B., F.R.S. Sir Richard A. S. Redmayne, K.C.B., M.Sc.
dmiralty Selection Board for the Appointment of Assistant Civil Engineers	Sir Alexander Gibb, G.B.E., C.B., F.R.S. Sir Leopold H. Savile, K.C.B.

Department of Scientific and Industrial Research :—

ommittee on Testing Work for the Building Industry	The President.
echanisation Board, Army Council	W. G. Wilson, C.M.G., B.A.
dvisory Panel on Transport (Ministry of Transport)	O. R. H. Bury. Col. R. E. B. Crompton, C.B., F.R.S. Sir John P. Griffith, M.A.I. J. A. Saner.
ome Office Sub-Committee on Air Raid Precautions.	Sir Leopold H. Savile, K.C.B.
cience Museum Advisory Council, Board of Education	Professor C. E. Inglis, O.B.E., M.A., LL.D., F.R.S.
ourt of the University of Bristol	Raymond Carpmael, O.B.E.
ourt of the University of Liverpool	Thomas Molyneux, O.B.E.
ourt of the University of Sheffield	Sir William H. Ellis, G.B.E., D.Eng.
overning Body of the Imperial College of Science and Technology	Sir George W. Humphreys, K.B.E.
ouncil of the City and Guilds of London Institute	The President.
ity and Guilds Fellowship Selection Committee	E. G. Walker, B.Sc.
ourt of University College, Southampton	F. E. Wentworth-Sheilds, O.B.E. A. C. Hughes, B.Sc.
overning Body of the School of Metalliferous Mining, Cornwall	J. G. Lawn, C.B.E.
homason College, Roorkee, Advisory Council	Gerald Lacey, B.Sc.
ld Centralians Committee on Memorial to Dr. W. C. Unwin	Sir Richard A. S. Redmayne, K.C.B., M.Sc. Sir Charles L. Morgan, C.B.E., D.Eng. The Secretary.

Engineering Advisory Committee, Huddersfield Engineering College	V. Turner. J. Urquhart.
Engineering Joint Council	Sir Clement D. M. Hindle[y], K.C.I.E., M.A. David Anderson, LL.D., B.Sc.
Engineering Public Relations Committee	Sir Clement D. M. Hindle[y], K.C.I.E., M.A.
Diesel Engine Users' Association	W. A. Tookey. H. R. Ricardo, B.A., F.R.[S.]
Parliamentary Science Committee	Sir George W. Humphrey[s], K.B.E. Sir Murdoch MacDonald[,] K.C.M.G., C.B., M.P.
Council of the London Society	T. H. Bailey.
Governing Body of the Denning Trust	A. E. Cornewall-Walker.
Tribunal of Appeal, London Building Act, 1930.	Sir Cyril R. S. Kirkpatric[k]
Joint Committee on Materials and their Testing.	R. H. H. Stanger.
Alloys and Iron Research Committee of the Institution of Mechanical Engineers	Sir Robert A. Hadfield, Bt[.,] D.Sc., D.Met., F.R.S.
British Cast Iron Research Association	Sir Robert A. Hadfield, Bt[.,] D.Sc., D.Met., F.R.S.
Permanent Commission of International Navigation Congresses	Sir Cyril R. S. Kirkpatrick[.] N. G. Gedye, O.B.E., B.S[c.]
Permanent International Association of Road Congresses, British Organizing Committee	F. C. Cook, C.B., D.S.O[.,] M.C.
Advisory Board, School of Planning and Research for National Development	David Anderson, LL.D[.,] B.Sc.
General Organizing Committee, 18th International Geological Congress, 1940.	Sir Richard A. S. Re[d]mayne, K.C.B., M.Sc.
Joint Committee of The Institution and The Institution of Structural Engineers on Code of Practice for Structural Steelwork	Professor J. F. Baker, M.A[.,] D.Sc. Professor C. Batho, D.Sc[.,] B.Eng. H. P. Budgen, Ph.D., M.S[c.] Ralph Freeman. B. L. Hurst. Professor A. J. S. Pippar[d,] M.B.E., D.Sc. J. D. Vaughan, M.Sc.

stitution of Mechanical Engineers, General Committee, Lubrication and Lubricants	S. B. Donkin.
orld Power Conference, British National Committee	S. B. Donkin.
orld Power Conference, International Sub-Committee on Special Cements	W. T. Halcrow.
ernational Electrotechnical Commission on Steam Turbines ernational Electrotechnical Commission	I. V. Robinson.
Advisory Committee on Internal-Combustion Engines.	W. A. Tookey.
in Committee of the Canadian Engineering Standards Association	H. H. Vaughan.

The Institution is represented as follows on Councils of the British ndards Institution :—

neral Council	Sir Cyril R. S. Kirkpatrick.
gineering Divisional Council	S. B. Donkin. Sir Clement D. M. Hindley, K.C.I.E., M.A. W. T. Halcrow.

d has also representatives on numerous Committees, Sub-Committees, d Panels.

The Council nominated Mr. S. B. Donkin to represent The Institution the Celebration of the Centenary of the Foundation of the Swiss ciety of Engineers and Architects, which was held at Berne on the 4th d 5th September, 1937; Dr. J. J. C. Bradfield, C.M.G., M.E., Member of uncil resident in Australia, to represent The Institution at an Engineering nference held in connexion with the celebrations of the 150th anniverry of the foundation of Australia, at Sydney in March, 1938; Professor E. Inglis, O.B.E., M.A., LL.D., F.R.S., Professor A. J. Sutton Pippard, B.E., D.Sc., and Mr. R. J. Durley, M.B.E., B.Sc., Ma.E., MM. Inst. C.E., represent The Institution at the Fifth International Congress for plied Mechanics to be held at the Massachusetts Institute of Technology, S.A., in September, 1938; and Mr. W. H. Morgan, D.S.O., M. Inst. E., to represent The Institution at the International Road Congress to be ld at the Hague in June, 1938.

Sir Alexander Gibb (President 1936–37) represented The Institution the celebration of the 50th anniversary of the foundation of the gineering Institute of Canada held in June, 1937.

Kelvin Medal.—The Kelvin Medal Award Committee, representative eight engineering institutions in this country, under the chairmanship Mr. Donkin, has awarded the Kelvin Medal for 1938 to Sir Joseph J. omson, O.M., D.Sc., F.R.S., in recognition of the eminent services he

has rendered to engineering science. The Council had pleasure in plac the Great Hall at the disposal of the Award Committee for the presentat of the medal by Lord Rayleigh, M.A., D.Sc., F.R.S., on the 3rd May.

James Alfred Ewing Medal.—The first award of the James Alf Ewing Medal for specially meritorious contributions in the field of engine ing research has been made to Mr. Charles Samuel Franklin, on recommendation of Sir Alexander Gibb, President 1936–37, and Sir Willi Bragg, President of the Royal Society, following suggestions put forw in their personal capacities by the Presidents of the Institutions Mechanical and Electrical Engineers and Naval Architects. The p sentation was made by Mr. Donkin on the 3rd May.

Scholarships.—A William Lindley Scholarship of £80 per annum 3 years has been awarded to Mr. John Napier Cooper to assist him pursue a course of engineering study at Cambridge University. A Palr Scholarship of £45 per annum for 3 years has been awarded to Paul Graham Mann to assist him to pursue a course of medical study Cambridge University, and a similar scholarship of the value of £40 1 year has been awarded to Mr. Charles Frederick Carter to assist h to pursue a course of mathematical study at Cambridge University.

Following a legacy bequeathed to The Institution by Mr. G. Dennison, M. Inst. C.E., the Council have established a scholarship approximately £20 a year, to be known as the Dennison Scholarship, op to Students of The Institution of limited means to assist them to stu civil engineering at a university or approved institution, preferen being given to candidates who are studying for Sections A and B of t Associate Membership Examination. The first award of this scholarsh has been made to Mr. John Kenneth Dawson, Stud. Inst. C.E.

Charles Hawksley Prize.—On the report of the judges (the Preside and the President of the Royal Institute of British Architects), the Coun have awarded a Charles Hawksley Prize of the value of £150 to Mr. Jan Louis Matheson, M.Sc., Assoc. M. Inst. C.E., for his design of a multip storied public garage.

Professional Records.—The Council have decided to institute systematic and official record of each Corporate Member of The Instituti and, with the object of obtaining detailed particulars of the activities the members, a schedule has been issued inviting them to state particular branches of engineering in which they specialize, toget with the work they have been engaged on since their election or transf The Council would earnestly ask members to complete and return th schedules, so that this record may be as complete as possible.

Architects' Registration Bill.—Following the reintroduction Parliament of a Bill to restrict the use of the word "Architect" to th who are Registered Architects, the Council decided to take joint act with the Institution of Structural Engineers and the Institution Municipal and County Engineers to obtain, if possible, the safeguardin

position of engineers in connexion with the proposed legislation, and oint Committee was formed for the purpose. Up to the present it is lerstood that the Committee has not been able to obtain, during passage of the Bill through the House of Commons, the desired safe-rds.

L.C.C. Building By-laws.—The Joint Committee of The Institution, Royal Institute of British Architects, the Chartered Surveyors' titution and the Institution of Structural Engineers, which was pointed to examine the Building By-laws and By-laws for the Use of nber proposed by the London County Council, have continued their iberations. The By-laws in question have now been issued by the inty Council, and it is satisfactory to note that many of the suggestions forward by the Joint Committee have been embodied in the published -laws. At the request of the London County Council, the Joint Com-ttee have also discussed with that body proposed regulations dealing h the use of electric (metal) arc welding and the use of steel reinforce-nt for reinforced concrete, and have made a number of suggestions ich have been accepted by the County Council.

National Defence.—The Council are in touch with certain Govern-nt Departments with regard to matters of national defence, and with ard to air-raid precautions, with a view to offering The Institution's operation as far as this may be possible.

International Engineering Congress.—The preparations for the ernational Engineering Congress to be held at Glasgow from the 21st the 24th June, in which The Institution is participating with a number other engineering societies, are well advanced. Addresses by prominent gineers from this country and from abroad will be given, and visits works and certain social functions are being arranged. The Congress l be opened by the President, Lord Weir, P.C., G.C.B.

Building.—The north-west corner of the building was completed in time the Coronation and the building was suitably decorated and floodlit. e occasion of the Conversazione, which was held on the 2nd June, and s attended by 2,871 members and guests, was made the opportunity the unveiling, by Sir Alexander Gibb, President 1936–37, of a tablet mmemorating Thomas Telford and the debt which The Institution es to him for supplying the nucleus of the present Library.

The Council have been pleased to afford accommodation in the stitution building for meetings of various engineering societies, and the stitution of Mechanical Engineers, the Law Society and the Civil Service mmission have had the use of certain rooms for examination purposes. number of official inquiries by the Ministry of Transport, the Board Trade and the Treasury have been held at the Institution.

Annual Dinner.—The annual dinner was held on the 15th March, en 701 members and guests attended.

Accounts.—The Accounts for the year ending 31st March, 1938,

which have been duly audited, are detailed in Appendix II of this Rep[ort]
and may be summarized briefly as follows :—

The *Total Income* for the year amounted to . . £44,[...]
(as compared with £43,411 last year) including £302 for Income Tax recovered. Subscriptions, Entrance and Examinations fees totalled £42,296 (as compared with £41,719 last year) and Dividends and Interest received amounted to £1,390 (as compared with £1,424 last year).

The *Total Expenditure* charged against the year's income amounted to . . . . £45,[...]
(as compared with £44,095 last year) but it included Provisions of £14,600 (viz. £12,000 for Publications Account and £2,600 for Research Reserve) as compared with £12,600 last year.

The *Revenue Account* therefore results in an *adverse balance* of . . . . £1,[...]
which has been carried to the debit of the Revenue Account from which has been deducted the credit balance of the General and Contingency Reserve £613, leaving a final debit balance of £1,049 as shown on the Balance Sheet.

The actual expenditure during the year on "Publications Accoun[t]" amounted to £19,493 (compared with £18,159 last year), of which £12,[...] represented the cost of the Journal (including the cost of the Mar[ch] 1937, issue). This expenditure was relieved by credits for advertisemen[ts], sales, etc., of £4,650 (against £4,494 last year), leaving the net expendit[ure] for the year at £14,843 (compared with £13,665). This amount, howe[ver], was £2,843 more than the £12,000 provision credited, thereby increas[ing] the overspent balance on this account (from £6,080 last year) to £8,[...] at 31st March, 1938, as shown by the balance sheet. This excess exp[en]diture falls to be liquidated in the future.

The *Research Reserve* credit balance has been reduced by £342 du[ring] the year, viz. from £2,207 to £1,865.

The expenditure incurred amounted to £3,563 whereas the cre[dits] (made up of the appropriation from Revenue Account of £2,600, [and] contributions by outside bodies of £622) totalled £3,222.

The Repairs and Renewals credit balance has been reduced by £[...] during the year, viz. from £6,103 to £5,216.

On Trust Funds Income Account there was received a total of £1[...] (against £1,235 last year) and the expenditure amounted to £996 (£73[...]).

Contributions amounting to £627 (£656) were received from Home [and] Overseas Harbour and Dock Authorities towards the cost of the rese[arch] into the Deterioration of Structures exposed to Sea Action. The expe[ndi]ture during the year was £537 (£840).

Library.—During the year 618 volumes were presented to the [Libr]ary and 211 were purchased, making a total, on the 31st March, 1938, [of] 3,129.

The number of applications received for books on loan was 2,042, an [incr]ease of 59 on the preceding session. The demand for the Loan [Libr]ary Catalogue, published in 1935, continues, and a supplementary [list] is in course of preparation.

The furnishing of the Tait Room, as a part of the library devoted to [boo]ks on legal matters, has now been completed, and a suitable inscription [and] photographic portrait of the late Dr. W. A. Tait placed there on [reco]rd.

Gifts.—Sir Alexander Gibb, President 1936–37, has presented to The [Ins]titution his portrait, painted by Sir William Rothenstein. Other gifts [rece]ived by The Institution during the year include photographs of Dr. H. T. Tudsbery, Honorary Secretary, and of the late Dr. H. H. Jeff[cott], presented respectively by Mr. M. T. Tudsbery, M. Inst. C.E., and [Mrs]. Jeffcott, a photograph of a novel short-wave wireless communication [app]aratus constructed for use in Northern Rhodesia, signed by the late [Mar]chese Marconi, presented by Sir Cyril Kirkpatrick, Past-President; and [a fr]amed proof copy of an etching signed by the artist, Cyril H. Barraud, [of] the boiler house interior at the Kearsley power-station of the Lan[cas]hire Electric Power Co., presented by Messrs. Babcock and Wilcox, [thr]ough Mr. J. O. Twinberrow, Assoc. M. Inst. C.E.

A special donation of 20 guineas for the purchase of an easy chair [in m]emory of his father, the late Sir Frederick Palmer, Past-President, [was] received from Mr. J. E. G. Palmer, M.A., Assoc. M. Inst. C.E.

Examinations.—The number of candidates presenting themselves [for] the October, 1937, Examinations was 442 (as compared with 434 last [yea]r), namely, 78 for the Preliminary Examination and 364 for the Associate [Me]mbership Examination. The entries for the April, 1938, Examinations [wer]e 156 for the Preliminary Examination and 620 for the Associate [Me]mbership Examination, a total of 776 (as compared with a total of 704 [last] year).

Bayliss Prizes of the value of £15 have been awarded to Mr. Shanti [Sw]arup Varma, Stud. Inst. C.E., and to Mr. Ronald Kerridge, Stud. [Ins]t. C.E., in respect of Sections A and B of the Associate Membership [Exa]mination for April and October, 1937, respectively, and Mr. Gilbert [Fra]nk Norris, Stud. Inst. C.E., has received honourable mention in [con]nexion with the former examination.

With a view to reducing the duplication of examinations, the Council, [wh]ile bearing in mind the necessity for maintaining the standard of [qua]lifications necessary for election into The Institution, have extended [the] list of qualifications exempting in whole or in part from the Institu[tio]n examinations to include Corporate Members of the following

Institutions who have qualified by examination under the curr
regulations of the respective bodies :—

The Institution of Mechanical Engineers.
The Institution of Electrical Engineers.
The Institution of Structural Engineers.
The Institution of Municipal and County Engineers.

With the same object the Council now recognize the following Certifica
for the purpose of exemptions from the Institution examinations :—

First Class Certificate of Competency under the 1911 Coal Mines A
Higher National Certificates in Engineering.
Ordinary National Certificates in Engineering.

The Council have also given close consideration to the question of rec
nition of certain degrees of Indian Universities for the purpose of exempt
from Sections A and B of the Associate Membership Examination.
application was received from Bombay University, as a result of whi
the Honours degree in Civil Engineering of that University, if obtai
under certain specified conditions, is to be so accepted.

Officers and Staff.—Special mention must be made of the regret
death on the 11th December, 1937, of Mr. Percival Davis Griffiths, w
had been one of the two Auditors of The Institution since 1903 ; a
of the fact that Sir Alan Rae Smith, O.B.E., has been nominated
succeed Mr. Griffiths.

Mr. H. T. Griggs, a member of the Institution Staff, having attain
the age-limit under the staff pensions scheme, retires in June this y
after completing 47 years of loyal and valued service to The Institution

Elections, Transfers, and Admissions.—On the recommendation
the Council the following have been elected Honorary Members by v
of the members present at an Ordinary Meeting :—

His Majesty Leopold III, K.G., King of the Belgians ;
His Royal Highness Gustaf Adolf, Duke of Skåne, G.C.B., G.C.V.
Crown Prince of Sweden ;
Sir Robert Elliott-Cooper, K.C.B. (*Past-President*) ;
Sir Frank Edward Smith, K.C.B., C.B.E., D.Sc., LL.D., F.R.S.

The Council record with satisfaction that 540 new proposals
election were received during the year, and 132 postponed from previ
sessions—mainly pending compliance by the candidates with the exami
tion requirements—were brought forward for final consideration, mak
a total of 672 applications dealt with by the Council. 103 recommen
tions for the transfer of Associate Members to the class of Members w
also considered, and 632 candidates were admitted to Studentship. Th
figures show a substantial increase on those for last year.

For the year ending the 31st March, 1938, the elections comprise
Honorary Members, 7 Members, 337 Associate Members and 3 Associat
572 candidates were admitted as Students, and the names of 2 Memb

Associate Members, and 1 Student were restored to the Roll. From addition of 940 must be deducted the deaths, resignations, erasures over-age Students, the member elected an Honorary Member and the dents elected Associate Members, amounting to 547 in all, showing a increase of 393; 85 Associate Members have been transferred to the s of full members.

The Roll.—The Roll of The Institution on the 31st March, 1938, od at 12,141. The changes which took place during the year ended on t date are shown in the following Table :—

	1 April, 1936, to 31 March, 1937.						1 April, 1937, to 31 March, 1938.					
	Honorary Members.	Members.	Associate Members.	Associates.	Students.	Totals.	Honorary Members.	Members.	Associate Members.	Associates.	Students.	Totals.
nbers at ommence-ment	14	2261	7121	58	1900	11,354	17	2288	7199	57	2187	11,748
nsfers—ssociate Members Members	..	+90	−90	..	..		..	85	85	..	..	
lember to ssociate Member	..	− 1	+ 1	..	..		..	..	..	..	..	
ctions	5	17	297	1	..	+791	4	7	337	3	..	+ 940
nissions	..	..	..	..	454		..	..	..	..	572	
tored to Roll	..	..	15	..	2		..	2	14	..	1	
eased	1	60	67	1	2		2	64	61	3	3	
signed	..	14	44	1	20		..	26	29	2	9	
sed	1	4	32	..	14		..	5	23	1	17	
cted as an Honorary Member	..	1	..	..	..		..	1	..	..	..	
cted as Associate Members	..	..	..	..	129	− 397	..	..	..	..	177	− 547
noved—ver age	..	..	..	..	..		..	..	..	..	116	
led to omplete	..	..	2	..	3		..	..	3	..	3	
led to omply Student-hip)	..	..	..	—	1		..	..	..	..	2	
						+ 394						+ 393
mbers at ermination	17	2288	7199	57	2187	11,748	19	2286	7349	54	2433	12,141

The Roll at this date is 12,188.

The Council record with especial regret the deaths of *Marchese* glielmo Marconi, G.C.V.O., D.Sc., LL.D. and *The Rt. Hon. Lord* Rutherrd, O.M., D.Sc., F.R.S., Honorary Members; Robert West Holmes,

I.S.O., Hugh Henry Gordon Mitchell, O.B.E., and Alexander Forres Stewart, former Members of Council.

The full list of deaths is as follows (*E.* refers to election, *T.* to transfe and *A.* to admission) :—

Deaths.—*Honorary Members* (2).—*Marchese* Guglielmo Marconi, G.C.V.O., D. LL.D. (E. 1925) ; *The Rt. Hon. Lord* Rutherford, O.M., D.Sc., F.R.S. (E. 1928).

Members (64).—Robert Adam, O.B.E. (E. 1891. T. 1906) ; Arthur Thon Arnall, B.Sc. (E. 1913. T. 1922) ; William Barrington (E. 1883. T. 1891) ; Ed Thomas Beard (E. 1900. T. 1905) ; *Sir* John Ferguson Bell (E. 1889. T. 190 Arthur Frederick Bennett (E. 1917) ; John Richard Blacker (E. 1893. T. 191 *Sir* Charles Bright, F.R.S.E. (E. 1889. T. 1911) ; Samuel Edwin Burgess (E. 18 T. 1899) ; Walter Henry Cobley, I.S.O. (E. 1877. T. 1890) ; Hugh Lincoln Coo (E. 1929) ; Richard Edward Synge Cooper (E. 1895. T. 1903) ; Frank Stuart Court (E. 1876. T. 1889) ; Stanley De Brath (E. 1886. T. 1894) ; *Sir* John Dewran G.B.E. (E. 1884. T. 1899) ; Edward Dodd (E. 1901. T. 1910) ; Harrison Pres Eddy (E. 1929) ; Walter Eraut, C.B.E. (E. 1900. T. 1918) ; Henry Farrant, E (E. 1904. T. 1928) ; James Fletcher (E. 1906. T. 1919) ; Hugh Barron Fraser 1902) ; Ralph Ernest Gibson (E. 1900. T. 1919) ; Samuel Slater Grimley (E. 18 T. 1911) ; John Parker Harris (E. 1895. T. 1905) ; Bertram Lionel Harvey, B (E. 1920. T. 1935) ; Thomas William Alfred Hayward (E. 1902. T. 1910) ; Ha Heckford (E. 1900. T. 1912) ; Huon Holden, F.C.H. (E. 1906. T. 1925) ; Rob West Holmes, I.S.O. (E. 1887. T. 1897) (*former Member of Council*) ; Frank Hud (E. 1880. T. 1888) ; Henry Adin Hull (E. 1896. T. 1911) ; Henry Homan Jeffc B.A.I., Sc.D. (E. 1910. T. 1933) (*Secretary of The Institution*) ; Henry Charles Jenk (E. 1891. T. 1929) ; John Sinclair MacLachlan, B.A., B.E. (E. 1906. T. 193 John Norman Campbell MacTaggart, M.E. (E. 1902. T. 1914) ; Hubert Bin Marten (E. 1891. T. 1904) ; Frank Massie (E. 1888. T. 1906) ; Hugh Henry Gor Mitchell, O.B.E. (E. 1910) (*former Member of Council*) ; Frederic Albert Mol (E. 1916) ; Robert Thomas Moore, D.Sc. (E. 1915) ; Charles Edward Newton (E. 189 Arthur Cadlick Pain (E. 1870. T. 1877) ; Reginald Godfrey Peckitt, C.B.E., E (E. 1900. T. 1913) ; Arthur Lancelot Bonner Plunkett (E. 1922. T. 1929) ; J Archibald Polwhele, O.B.E. (E. 1897. T. 1907) ; Sidney Preston, C.I.E., C.E (E. 1876. T. 1914) ; Charles Henry Priestley (E. 1886. T. 1902) ; William Carst Reid (E. 1917) ; Samuel John Sarjant (E. 1908) ; Ernest Edward Sawyer, M (E. 1876. T. 1880) ; Charles Louis Sim (E. 1880. T. 1891) ; *Sir* Ismail Sirry, Pas K.C.M.G. (E. 1914) ; Arthur Spyer (E. 1904) ; Alexander Forrester Stewart (E. 19 (*former Member of Council*) ; John Edwin Stewart (E. 1894. T. 1909) ; Fra William Harold Stileman (E. 1909. T. 1920) ; Hubert Tremelling (E. 1904. T. 191 Gilbert Kennedy Trench (E. 1886. T. 1910) ; *Sir* Seymour Biscoe Tritton, K.E (E. 1893. T. 1896) ; John Clough Vaudrey (E. 1880. T. 1893) ; Herbert Wa (E. 1884. T. 1909) ; James Falshaw Watson (E. 1898. T. 1912) ; Charles Ford Wheeler, B.A., B.E. (E. 1911. T. 1937) ; John Huw Williams (E. 1900. T. 1914

Associate Members (61).—*Senor* Rodolfo de Arteaga (E. 1876) ; James Rae Bater (E. 1887) ; Jesse Haigh Baxter (E. 1913) ; Davis Edmondson Benson (E. 1886) ; J Torrington Blatchford, B.E. (E. 1936) ; John Brown, B.Sc. (E. 1905) ; Arthur Dod Chapman (E. 1883) ; Albert Victor Cole (E. 1917) ; Frederick George Cooke (E. 18 Bernard Alfred Martin Cooper (E. 1916) ; John Francis Costello, M.A., M.A.I. (E. 19 George Robert Cowdery (E. 1899) ; Samuel Cutler (E. 1905) ; Fred Doughty (E. 19 Frederick Jonathan Down (E. 1897) ; William Henry Elce (E. 1900) ; Tom Free Firr (E. 1900) ; Albert Augustus Gill (E. 1883) ; George Francis Carter Gordon, M (E. 1904) ; Herbert Boys Gregson (E. 1889) ; Arthur Franklin Guillemard, M (E. 1878) ; Francis Armitage Hardy (E. 1929) ; Irwin Joseph Howell (E. 1924) ; Edw Henry Hughes (E. 1914) ; Herbert William Hughes (E. 1891) ; Donald Fred Hulse (E. 1927) ; John Christian Jamieson, M.A. (E. 1906) ; Alfred John Jen (E. 1894) ; Edward Dukinfield Jones (E. 1884) ; Henry John Alfred Jones (E. 19

derick William Knewstubb (*E.* 1905); George Taylor Leithhead, B.Sc. (*E.* 1935); lliam Arthur Linskill, M.Sc. (*E.* 1905); Walter Linton (*E.* 1906); William Alexander on, B.Sc. (*E.* 1927); Jeremiah James Macdonald, B.Sc. (*E.* 1924); Thomas John lcolm Macfarlane, C.M.G. (*E.* 1884); John Livingstone Miller, B.Sc. (*E.* 1931); ginald Joseph Mitchell, C.B.E. (*E.* 1920); James William Nunn (*E.* 1905); Alfred rk Oliver (*E.* 1893); William McCammon Paterson, B.Sc. (*E.* 1927); William John kins (*E.* 1906); Alan Reynolds (*E.* 1906); Thomas Imrie Rhodes (*E.* 1918); John nley Rosbotham (*E.* 1936); Richard Underdown Shaxby, B.A., B.Sc. (*E.* 1904); *mmander* Francis Henry Eldred Shipton, O.B.E., R.N. (ret.) (*E.* 1904); John Henry inson (*E.* 1885); Thomas James Taplin (*E.* 1913); William Arthur Thain (*E.* 1902); n Whiteman Morland Topley (*E.* 1906); Herbert Perkins Vacher (*E.* 1879); Robert lker, B.E. (*E.* 1891); Charles Theodore Hermann Weiss (*E.* 1892); Henry Lawrence eatley (*E.* 1894); James Whitaker (*E.* 1891); Lawrence Hersee Whitmore (*E.* 1880); nes Whyte (*E.* 1896); Cecil Brook Williams, B.Sc. (*E.* 1932); Francis Woodman lson (*E.* 1909).

Associates (3).—*Brig.-Gen.* James Dallas (*E.* 1891); *Rear-Admiral* Charles Edward nro (*E.* 1911); Leslie Robert Vigers (*E.* 1904).

Students (3).—David Lewis Davies (*A.* 1934); William Holt Roberts (*A.* 1934); lney John Stephens, B.A. (*A.* 1935).

The following resignations have been received :—

Members (26).—James Andrew (*E.* 1923); Philip Arnold Anthony, C.M.G. (*E.* 1910); rbert Jefcoate Atkinson, B.A.I. (*E.* 1896. *T.* 1902); Frederick William Bakewell 1919); Ernest Augustus William Barnard, O.B.E. (*E.* 1907); Charles Edward mner (*E.* 1898. *T.* 1905); Ernest Reynolds Briggs (*E.* 1906. *T.* 1919); Francis cnamara Calcutt (*E.* 1913); William Cleaver (*E.* 1910); Wallace Alan Douglas rding (*E.* 1904. *T.* 1922); George Patrick Hayes, O.B.E., B.A., B.E. (*E.* 1904. 1907); Walter Wellesley Hill, M.B.E. (*E.* 1908); Harry William Maclean Ives, .E. (*E.* 1892. *T.* 1913); Frederick William Lanchester, LL.D., F.R.S. (*E.* 1910); rnard Courtney Laws, D.Sc. (*E.* 1897. *T.* 1921); Malcolm Hunter Logan, O.B.E., C. (*E.* 1923); Verner White Livingston Macassey (*E.* 1912. *T.* 1925); William rnard MacCabe (*E.* 1894. *T.* 1902); Ernest Branwhite Martin, D.S.O. (*E.* 1896. 1913); Godfrey Wilson Moore (*E.* 1895. *T.* 1913); Matthew Alexander Murphy, B.E. (*E.* 1904. *T.* 1920); Geoffrey John Phillips (*E.* 1914); Harold Douglas Rice 1924); *Professor* Richard Stanfield, F.R.S.E. (*E.* 1891. *T.* 1900); Arthur Bennett ylor (*E.* 1913. *T.* 1934); William Johnston Thornhill, O.B.E. (*E.* 1927).

Associate Members (29).—Sidney à Court (*E.* 1889); Bening Mourant Arnold, S.O., M.A. (*E.* 1914); Hugh Macandrew Baikie, B.Sc. (*E.* 1916); Frederick Herbert ncroft (*E.* 1903); Malik Fateh Chand Batra, B.Sc. (*E.* 1933); Frederick Stuart omfield (*E.* 1927) (*since reinstated*); Walter Lonsdale Bosker (*E.* 1910); Charles mpbell Canney (*E.* 1911); William Conyngham Cantrell (*E.* 1914); Arthur Melvill se (*E.* 1924); Gabriel Garcés (*E.* 1918); William Gemmill (*E.* 1913); Frederick rnard Gibbard (*E.* 1905); Albert Victor Gibbings (*E.* 1913); William Ashburnham rris (*E.* 1913); Thomas Edward Ingoldby, B.A. (*E.* 1900); Cecil Daubeny Inman, B.E. (*E.* 1901); Reginald de Vere Irwin (*E.* 1920); William Trevor Jeffries (*E.* 1933); c Kaye-Parry, B.A.I. (*E.* 1914); Roger Ferdinand Vogel Leech (*E.* 1913); Joseph tchel Maclean (*E.* 1906); Gerald Riou Lillingston Malet (*E.* 1920); John Brooks x Mason (*E.* 1929); William Dudley Vere Monies, B.Sc. (*E.* 1916); Cyril George whouse (*E.* 1921); George Harold Pethick (*E.* 1905); Douglas Walter Julius venhill (*E.* 1910); George Muskett Saunders (*E.* 1911).

Associates (2).—John Willock Seymour, B.Sc. (*E.* 1933); John Symonds (*E.* 1912).

Students (9).—Samuel Cohen (*A.* 1935); William Robert Hall (*A.* 1931); George nest Langrish (*A.* 1931); Ewen Gordon McEwen, B.Sc. (*A.* 1936); Howel Griffith cholas, B.Sc. (*A.* 1936); Arthur Reynolds (*A.* 1928); Henry John Spencer, B.Sc. 1931); Ian Edward Main Watts, M.Sc. (*A.* 1936); Sidney Charles Wybrow 1928).

[APPENDIX.

APPE

BALANCE SHEE

	£	s.	d.	£	s.
To Institution Capital Account and Building Fund, *as detailed on pages 292 and 293*	..			416,323	16
,, Loan on Security of Institution Buildings—					
As per last account	3,705	0	9		
Less repaid during year	1,813	19	6		
				1,891	1
,, Creditors	..			2,759	15
,, Repairs and Renewals Reserve, *as detailed on pages 292 and 293*	..			5,216	10
,, Research Reserve, *as detailed on pages 298 and 299*	..			1,865	4
,, W. A. P. Tait Legacy, per last Account	648	3	4		
Less Expenditure on Library	474	19	9		
				173	3
,, Sea-Action Committee Account, *as detailed on pages 298 and 299*	..			2,047	14
,, Trust Funds, Capital and Income Accounts—					
Capital Accounts, *as detailed on pages 296 and 297, invested per contra*	38,017	6	3		
Income Accounts—Balances unexpended—*as detailed on pages 298 and 299*	2,766	3	4		
				40,783	9
,, Institution Revenue in Suspense—					
Proportion of 1938 Subscriptions applicable to the nine months from 1st April to 31st December, 1938	14,753	9	11		
Subscriptions received in advance	104	13	2		
				14,858	3
				£485,918	18

AU

We have audited the above Balance Sheet dated 31st March, 1938, and have is properly drawn up so as to exhibit a true and correct view of the state of The Ins shown by the books of The Institution.

London, 29th April, 1938.

IX.

ST MARCH, 1938.

			£ s. d.	£ s. d.
EXPENDITURE ON INSTITUTION BUILDING, INCLUDING COST OF SITE, *as per last account*			361,172 1 0	
d EXPENDITURE DURING THE YEAR ON THE COMPLETION OF THE BUILDING			14,595 15 10	
				375,767 16 10
INSTITUTION INVESTMENTS (including those held in respect of Repairs and Renewals Reserve) at or under cost, *as detailed on page 300*				50,294 0 4
NOTE.—*The value of these Investments at ruling prices on 31st March, 1938, amounted approximately to £47,407.*				
W. A. P. TAIT LEGACY—				
Cash at Bank				173 3 7
SEA-ACTION COMMITTEE ACCOUNT—				
Cash at Bank				2,047 14 5
TRUST FUNDS INVESTMENTS, ETC.—				
Capital :—				
Investments, *as detailed on pages 296 and 297*		38,015 4 3		
Cash at Bank		2 2 0		
			38,017 6 3	
Unexpended Income :—				
Investments, *as detailed on page 297*		214 8 2		
Cash at Bank—				
On Deposit a/c	2,500 0 0			
,, Current a/c	51 15 2			
		2,551 15 2		
			2,766 3 4	
				40,783 9 7
DEBTORS				1,477 13 0
CASH AT BANK AND IN HAND—				
Deposit and Current Accounts			5,393 13 6	
In Hand			10 0 0	
				5,403 13 6
REVENUE ACCOUNT—				
Debit Balance as per this year's Revenue Account			1,661 12 2	
Less Balance of General and Contingency Reserve per last account			613 0 1	
			1,048 12 1	
PUBLICATIONS ACCOUNT—				
Balance overspent to date, *per page 292*			8,922 15 0	
				9,971 7 1
				£485,918 18 4

E. GRAHAM CLARK, *Secretary.*

T.

nformation and explanations we have required. In our opinion such Balance Sheet ccording to the best of our information and the explanations given to us, and as

ALAN RAE SMITH } AUDITORS.
E. W. MONKHOUSE }

INSTITUTION CAPITAL ACCOU

	£	s.
To Balance *carried down*	416,323	16
	£416,323	16

RESERVE FOR REPAIRS AND RENEWALS

	£	s.
To Expenditure during the Year	2,089	4
,, Balance *carried down*	5,216	10
	£7,305	14

PUBLICATIO

	£	s.	d.	£	s.
To Balance, *per last account*				6,079	17
,, Expenditure during the Year—					
Journal	12,169	16	10		
Minutes of Proceedings	1,976	4	8		
Charters, By-laws and Lists of Members	422	11	10		
Engineering Abstracts	1,349	10	9		
Salaries, Clerical Pay and Pensions Premiums	3,234	15	7		
Lecture	105	0	0		
Reporting	55	3	0		
Excerpts	179	15	1		
	19,492	17	9		
Less Credits for Advertisements, Sales, Contributions, etc.	4,650	0	7		
				14,842	17
				£20,922	15
To Balance *brought down, as per Balance Sheet, page 291*				£8,922	15

D BUILDING FUND, 31st MARCH, 1938.

	£	s.	d.
Balance, *per last account*	416,233	12	10
Legacy under the Will of S. S. Grimley	90	3	3
	£416,323	16	1
Balance *brought down, as per Balance Sheet, page 290*	£416,323	16	1

RUCTURE, FURNITURE, FITTINGS AND MACHINERY.

	£	s.	d.
Balance, *per last account*	6,103	4	1
Institution Revenue Account—Amount provided for the year—*per page 294*	1,000	0	0
Interest on Investments	180	5	8
Income Tax Refunded	22	5	2
	£7,305	14	11
Balance *brought down, as per Balance Sheet, page 290*	£5,216	10	8

COUNT.

	£	s.	d.
Institution Revenue Account—Amount provided for the year—*per page 294*	12,000	0	0
Balance, *carried down* (being Excess of net Expenditure over Provision)	8,922	15	0
	£20,922	15	0

INSTITUTION REVENUE ACC

EXPENDITURE.

1936-37 £		£	s.	d.	£
	To HOUSE AND ESTABLISHMENT CHARGES—				
	Rates, Health, Unemployment and other Insurances	6,099	2	6	
	Electric Lighting and Power, Water-Supply, Warming, Ventilating and Telephone	673	19	5	
	Cleaning and Household Expenses.	1,042	3	9	
	Refreshments and Assistance at Meetings . . .	163	5	8	
8,177					7,978
	,, REPAIRS AND RENEWALS RESERVE—				
1,000	Amount provided for the year, *per page 293* . . .	..			1,000
	,, SALARIES, WAGES AND RETIRING ALLOWANCES—				
	Salaries	2,490	13	4	
	Retiring Allowances	1,605	0	0	
	Clerks, Messengers and Housekeeper	5,223	15	11	
10,189					9,319
	,, PREMIUMS ON POLICIES FOR STAFF PENSIONS—				
1,368	Portion paid by the Institution	..			1,260
	,, STATIONERY, POSTAGES, ETC.—				
	Stationery and Printing	1,324	9	10	
	Postages, Telegrams and Parcels	1,004	3	0	
2,012					2,328
	,, PUBLICATIONS ACCOUNT—				
10,000	Amount provided for the year, *per page 293* . . .	..			12,000
	,, RESEARCH RESERVE—				
2,600	Amount provided for the year, *per page 299* . . .	..			2,600
	,, LIBRARY—				
	Books and Periodicals	501	1	5	
	Clerical Pay and Pensions Premiums	997	10	6	
1,540					1,498
	,, EXAMINATION EXPENSES—				
	Examiners, Printing and General	1,891	7	8	
	Salaries, Clerical Pay and Pensions Premiums . .	1,697	13	2	
	Postages	134	8	4	
3,606					3,723
1,217	,, CONVERSAZIONE AND ANNUAL DINNER	..			1,412
	,, DIPLOMAS AND MEDALS—				
	Diplomas	47	10	0	
	Watt Medal	22	2	6	
	James Prescott Joule Medal Inscription	0	9	0	
67					70
	,, LOCAL ASSOCIATIONS—				
1,224	Grants to Local Associations, etc.	..			1,376
	,, CONTRIBUTIONS TOWARDS ADVISORY COMMITTEES IN				
100	THE DOMINIONS	..			104
	,, GRANTS AND CONTRIBUTIONS—				
	Engineering Public Relations Fund	95	0	0	
	British Standards Institution	50	0	0	
	Engineering Joint Council	12	10	0	
	Westminster Hospital	10	10	0	
	World Power Conference	3	3	0	
458					171
	,, LEGAL AND OTHER PROFESSIONAL CHARGES—				
	Legal Charges	195	14	9	
	Audit Fee	183	15	0	
	Engineers' and Surveyors' Charges	53	5	9	
218					432
135	,, TRAVELLING EXPENSES TO COMMITTEES	..			111
23	,, MEMORIAL SERVICE, ADDRESSES, ETC.	..			30
	,, CORONATION EXPENSES	..			214
161	,, INTEREST ON LOAN	..			83
£44,095					£45,717

1st APRIL, 1937, TO 31st MARCH, 1938.

INCOME.

	£	s.	d.	£	s.	d.	1936–37 £
scriptions applicable to the Financial Year 1937–1938	..			33,713	6	9	*32,905*
rance Fees	..			5,005	18	0	*5,441*
e Composition	..			..			*100*
erest, Dividends, etc.—							
n Institution Investments	1,384	8	7				
n Deposit and Current Accounts	5	15	4				
ncome Tax refunded for the year 1936–7	301	11	9	1,691	15	8	*1,627*
amination Fees	..			3,577	11	2	*3,273*
rary Fund Donations	..			67	11	6	*65*
				44,056	3	1	*43,411*
lance, being Excess of Expenditure over Income for the Year as per Balance Sheet, *page 291*	..			1,661	12	2	*684*
				£45,717	15	3	*44,095*

TRUS[T...]

CAPITAL ACCOUNTS AND INVESTMENT THEREOF AND INVESTME[NT...]

Capital Accounts. £ s. d.		Investments. Capital. £ s. d.	Unexpended Income. £ s. d.
8,038 9 4	TELFORD FUND.		
	£8,738 13s. 0d. 2½% Consols . .	7,988 9 4	
	£50 16s. 11d. 3½% War Loan . .	50 0 0	
270 0 0	MANBY DONATION.		
	£250 London & North-Eastern Railway 4% 2nd Guaranteed Stock	270 0 0	
6,337 12 4	MILLER FUND.		
	£5,129 17s. 5d. 2½% Consols . .	4,850 2 4	
	£1,513 15s. 9d. 3½% War Loan. .	1,487 10 0	
500 0 0	HOWARD BEQUEST.		
	£352 11s. 5d. 2½% Consols . . } Cost of Medal Die . . . . }	500 0 0	
600 0 0	TREVITHICK MEMORIAL.		
	£103 2½% Consols	100 0 0	
	£506 5s. 7d. 3½% Conversion Loan 1961.	500 0 0	
540 0 0	CRAMPTON BEQUEST.		
	£512 15s. 11d. 2½% Consols. . .	500 0 0	
	£40 13s. 7d. 3½% War Loan . .	40 0 0	
1,234 14 0	JAMES FORREST LECTURE AND MEDAL FUND.		
	£465 Southern Railway 4% Debenture Stock	604 14 0	
	£667 5s. 8d. 3½% War Loan . .	630 0 0	
1,647 10 10	PALMER SCHOLARSHIP.		
	£1,650 10s. 0d. 3% Redemption Stock, 1986–1996	1,547 10 10	
	£100 9s. 8d. 3½% War Loan . .	100 0 0	
1,080 0 0	JOHN BAYLISS BEQUEST.		
	£1,013 17s. 10d. London County 3% Stock, 1920	1,000 0 0	
	£80 7s. 10d. 3½% War Loan . .	80 0 0	
1,318 11 8	THE INDIAN FUND.		
	£1,353 4s. 2d. 2½% Consols . . .	1,148 11 8	
	£171 13s. 3d. 3½% War Loan . .	170 0 0	
1,000 0 0	VERNON-HARCOURT BEQUEST.		
	£1,082 9s. 10d. London County 3% Stock, 1920	1,000 0 0	
22,566 18 2	*Carried forward*	22,566 18 2	

NDS.

UNEXPENDED INCOME AT 31ST MARCH, 1938.

Capital Accounts. £ s. d.		Investments. Capital. £ s. d.	Investments. Unexpended Income. £ s. d.
566 18 2	*Brought forward*	22,566 18 2	
300 0 0	WEBB BEQUEST.		
	£1,055 7s. 2d. Metropolitan Water Board 3% "B" Stock	1,000 0 0	
	£303 16s. 2d. 3½% War Loan	300 0 0	
733 1 10	WILLIAM LINDLEY FUND.		
	£1,214 London Midland & Scottish Railway 4% Debenture Stock	1,584 16 8	
	£1,109 2s. 9d. 4½% India Stock, 1950–1955	1,005 15 2	
	£151 9s. 7d. 3½% War Loan	142 10 0	
725 0 0	KELVIN MEDAL FUND.		
	£757 18s. 11d. 3½% War Loan	725 0 0	
250 0 0	CHARLES HAWKSLEY BEQUEST.		
	£955 Metropolitan Water Board 3% "B" Stock	573 0 0	
	£500 South Essex Waterworks 5% Preference Stock	435 0 0	
	£70 5% Sheffield Corporation Water Annuities; £40 4% Sheffield Corporation Water Annuities	1,992 0 0	
	£1,257 17s. 4d. 3½% War Loan	1,250 0 0	
,101 6 5	COOPERS HILL WAR MEMORIAL.		
	£1,239 15s. 0d. 3½% War Loan	1,101 6 5	
	£215 12s. 3d. 3½% War Loan	..	214 8 2
,570 4 0	C. C. LINDSAY CIVIL ENGINEERING SCHOLARSHIP FUND.		
	£3,500 3½% War Loan	3,570 4 0	
320 0 0	BAKER MEDAL FUND.		
	£290 5s. 8d. London County Cons. 4½% Stock, 1945–85	320 0 0	
809 11 0	JAMES ALFRED EWING MEDAL FUND.		
	£798 12s. 9d. Middlesex County Council 3% Stock, 1961–1966	807 9 0	
641 4 10	G. H. DENNISON FUND.		
	£706 3s. 2d. 3% Local Loans	641 4 10	
,017 6 3	*As per Balance Sheet, page 291*	*38,015 4 3	*214 8 2

TE.—**The value of these Investments at ruling prices on 31st March, 1938, amounted approximately to £35,722 and £219 respectively.*

TRUST FUNDS INCOME ACCOUNTS FRO

Trust Fund.	Balance at 1st April, 1937 £	s.	d.
Telford Fund	111	11	7
Manby Fund	8	15	10
Miller Fund	286	14	1
Howard Bequest	54	6	10
Trevithick Memorial	23	9	3
Crampton Bequest	3	7	10
James Forrest Lecture and Medal Fund	20	15	8
Palmer Scholarship Fund	38	6	9
John Bayliss Bequest	49	18	10
Indian Fund	31	18	6
Vernon-Harcourt Bequest	94	5	10
Webb Bequest	194	14	10
William Lindley Fund	584	18	2
Kelvin Medal Fund	97	17	5
Charles Hawksley Bequest	192	9	6
Coopers Hill War Memorial Fund	327	8	7
C. C. Lindsay Civil Engineering Scholarship Fund	273	11	10
Baker Medal Fund	30	10	9
James Alfred Ewing Medal Fund	11	14	6
G. H. Dennison Fund	1	14	11
R. E. S. Cooper Legacy	0	0	0
Totals	2,438	11	6

COMMITTEE ON THE DETERIORATION O

ACCOUNT FROM 1ST APRIL, 19

	£	s.
To Amount paid on behalf of or to the Committee during the year to 31st March, 1938	537	4
,, Balance *carried down*	2,047	14
	£2,584	19

RESEARC

	£	s.	d.	£	s.
To RESEARCH—					
Vibrated-Concrete Research	400	0	0		
Pile-Driving Research	187	10	0		
Earth-Pressures Research	200	0	0		
Wave-Pressures Research	309	10	0		
Simply-Supported Steel Bridges Research	350	0	0		
Fish-Passes Research	495	7	7		
Soil-Corrosion Research	200	0	0		
Reinforced-Concrete Structures Research	120	0	0		
Repeated-Stresses Research	50	0	0		
Breathing-Apparatus Research	50	0	0		
To ADMINISTRATION EXPENSES—				2,362	7
Travelling Expenses of Committees	273	5	1		
Salaries, Clerical Pay and Pensions Premiums	852	10	8		
Furniture	8	15	0		
Sundries, including printing, travelling, etc.	66	3	3		
				1,200	14
				3,563	1
To Balance *carried down*				1,865	4
				£5,428	5

APRIL, 1937, TO 31ST MARCH, 1938.

ncome: Including Income Tax refunded for the year 1936–1937.	Expenditure on Scholarships, Prizes, Lectures, etc.	Balance at 31st March, 1938.
£ s. d.	£ s. d.	£ s. d.
245 15 5	257 16 2	99 10 10
9 18 4	10 0 0	8 14 2
182 11 4	87 0 6	382 4 11
9 1 4	63 0 0	0 8 2
20 5 11	38 7 9	5 7 5
14 5 2	10 0 0	7 13 0
41 16 5	47 9 6	15 2 7
67 3 0	0 0 0	105 9 9
33 1 8	30 1 0	52 19 6
39 19 5	33 1 0	38 16 11
32 10 2	3 9 3	123 6 9
42 15 11	25 0 0	212 10 9
105 5 1	0 0 0	690 3 3
26 19 7	0 0 0	124 17 0
206 10 7	275 0 0	124 0 1
51 9 2	44 17 10	333 19 11
123 15 3	25 0 0	372 7 1
13 2 5	34 10 0	9 3 2
21 13 6	0 0 0	33 8 0
10 5 2	11 0 0	1 0 1
25 0 0	0 0 0	25 0 0
1,323 4 10	995 13 0	†2,766 3 4
		As per Balance Sheet, p. 290.

RUCTURES EXPOSED TO SEA ACTION.

31ST MARCH, 1938.

	£	s.	d.
Balance, as per last Account	1,947	13	0
Subscriptions	626	11	1
Interest on Deposit	10	15	2
	£2,584	19	3
Balance *brought down as per Balance Sheet, page 290*	2,047	14	5

ESERVE.

	£	s.	d.
Balance, as per last Account	2,206	11	7
Contributions from other Bodies	621	14	0
Institution Revenue Account—Amount provided for the year—*per page 294*	2,600	0	0
	£5,428	5	7
Balance *brought down as per Balance Sheet, page 290*	£1,865	4	0

† Of which £214 8*s.* 2*d.* is invested (*see page 297*).

INSTITUTION INVESTMENTS AT 31st MARCH, 1938 (INCLUDIN THOSE HELD IN RESPECT OF REPAIRS AND RENEWA RESERVE) AT COST.

£	s.	d.		£	s.
3,000	0	0	Metropolitan Water Board 3% "B" Stock	2,958	16
6,000	0	0	London and North Eastern Railway 4% Debenture Stock	7,749	18
6,000	0	0	London Midland and Scottish Railway 4% Debenture Stock	7,452	14
2,545	0	0	London Midland and Scottish Railway 4% Guaranteed Stock	1,976	7
5,994	15	2	3½% War Loan	3,586	11
2,720	5	5	London Passenger Transport Board 4½% "A" Stock .	3,327	9
3,809	0	2	3½% War Loan	3,824	8
452	0	0	London Midland and Scottish Railway 4% Guaranteed Stock	351	3
989	14	7	London Passenger Transport Board 4½% "A" Stock .	1,210	12
5,327	6	5	New Zealand 3% Stock, 1952–1955	5,334	7
9,400	0	0	Middlesex County Council 3% Redeemable Stock, 1961–1966.	9,391	11
470	4	3	3% Local Loans	461	3
			National Gas and Oil Engine Co., Ltd., 3,336 Ordinary Shares of £1	2,668	16
			As per Balance Sheet, page 291 . .	£50,294	0

NOTE.—*The value of these Investments at ruling prices on 31st March, 1938, amounted approximately to £47,407.*

Paper No. 5175.

"The Failure of Girders under Repeated Stresses." (Part 2.)

By Professor Frederick Charles Lea, O.B.E., D.Sc. (Eng.), M. Inst. C.E., and John Gwynne Whitman, M.Eng.

(*Ordered by the Council to be published with written discussion.*)[1]

TABLE OF CONTENTS.

Introduction.

two Papers recently published by The Institution,[2,3] the results of periments on the effect of repeated stresses on structural elements have een given. In the second of these Papers the results of preliminary periments on structural elements in the form of rolled steel joists tested a special machine, called the "girder-fatigue testing-machine," were ven, together with a description of the machine.

Before proceeding to the series of tests of which particulars are given this Paper, some modifications to the machine were carried out. A

[1] Correspondence on this Paper can be accepted until the 1st September, 1938, d will be published in the Institution Journal for October, 1938.—Sec. Inst. C.E.

[2] F. C. Lea, "Repeated Stresses on Structural Elements." Journal Inst. C.E., l. 4 (1936–37), p. 93. (November 1936.)

[3] F. C. Lea and J. G. Whitman, "The Failure of Girders under Repeated Stresses." id., vol. 7 (1937–38), p. 119. (November 1937.)

new motor was installed and the running speed was increased from
to 350 cycles per minute.

The very small movement that occurred in the plain phosphor-bron bearings fitted at the ends of the specimen made it difficult to lubric these bearings, and from the point of view of the purpose of the mach serious wear took place. They have been replaced by "Silentblo bearings, and these are operating satisfactorily.

The ring used for calibration of the specimens has been re-calibrat and the load–deflexion relation was found to be identical with th previously obtained.

This Paper describes tests on the complete series of girders, consisti of the following :—

(1) Series A. Rolled mild-steel joists, 5 inches by 3 inches by 11

(2) Series A1. Rolled mild-steel joists, 5 inches by 3 inches by 11 l with two $\frac{9}{16}$-inch diameter rivet-holes in the tension-flan (as shown in *Figs. 4*, p. 306).

(3) Series B. Rolled mild-steel joists, 5 inches by 3 inches by 11 with a butt-welded joint at mid-span.

Series B1. Rolled mild-steel joists, 5 inches by $2\frac{1}{2}$ inches 9 lb., with a butt-welded joint at mid-span.

(4) Series D. Rolled mild-steel joists, 5 inches by 3 inches by 11 l with a fillet-welded joint at mid-span. Cover-plates we fillet-welded on the flanges and on the web.

(5) Series E. Rolled mild-steel joists, 5 inches by 3 inches by 11 l with a joint at mid-span. Cover-plates were riveted on t flanges and on the web.

(6) Series C. Built-up welded girders, 5 inches by 3 inches, co sisting of web-plates fillet-welded to the flange-plates. The were tested as welded.

(7) Series C1. Similar girders to those of Series C, but tested af heat-treatment at a temperature of 650° C.

These specimens were tested on a span of 7 feet 6 inches, and were loaded that a length of 12 inches in the centre was subjected to const bending moment. All tests were run with zero minimum stress.

Tests of Rolled Mild-Steel Joists: Series A.

The mild-steel joists were all rolled at the same time, and with th were supplied six short lengths from which the section-modulus of girders was carefully determined. The mean value of the section-modu was 5·58 inch^3 units, and that of the second moment of area was 14·40 in units.

gue-Tests.

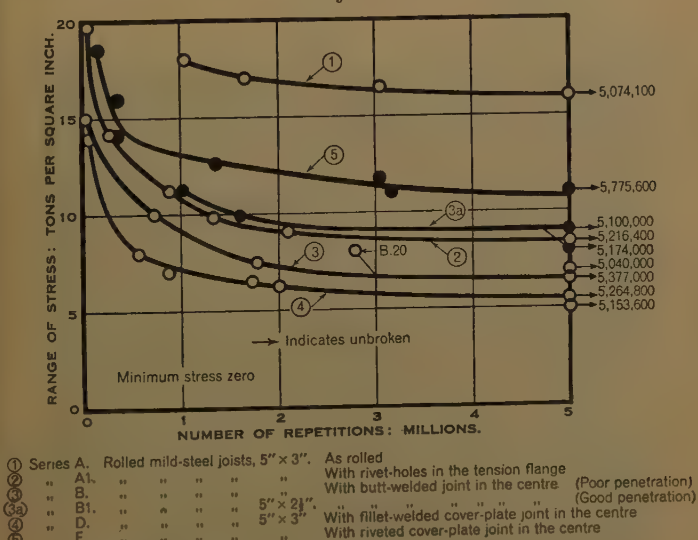
The results of the tests are shown in Table I and *Fig. 1* (curve No. 1). e fractures were of the usual fatigue type. As shown in *Fig. 2* (facing 304) the girder A.8 cracked in the centre of the tension-flange.

LE I.—FATIGUE-TESTS ON MILD-STEEL JOISTS 5 INCHES BY 3 INCHES BY 11 LB., AS ROLLED. SERIES A.

Specimen.	Range of stress: tons per square inch.	Number of repetitions.	Remarks.
. . . . .	18	1,042,900	Small amount of creep, broken.
. . . . .	16	5,074,100	No creep, unbroken.
. . . . .	16·5	3,427,000	Very slight initial creep, broken.
. . . . .	17	1,653,100	Small amount of initial creep; broken ¾ inch outside length of constant bending.

The fatigue-limit from zero minimum stress for more than 5 × 10^6 repetitions is tons per square inch.

Fig. 1.



FATIGUE-TESTS IN GIRDER-FATIGUE TESTING-MACHINE.

nsile Tests.

Two tensile specimens were turned from the flanges of girder A.8; e results of the tests are shown in Table II, p. 304.

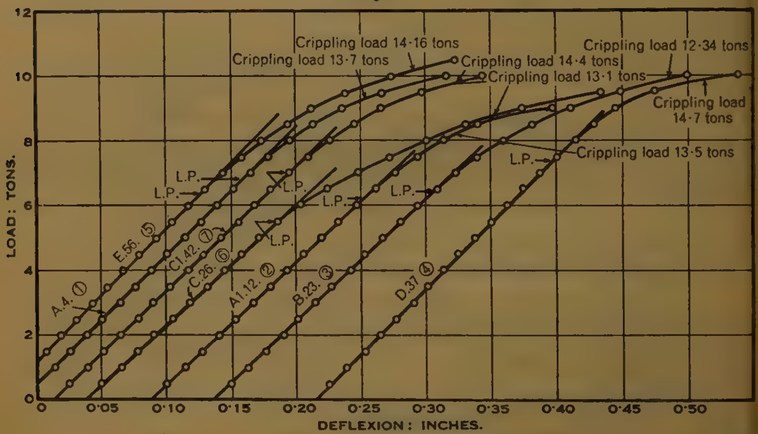
TABLE II.—TENSILE TESTS ON TWO SPECIMENS CUT FROM A.8.
(GAUGE-LENGTH 2 INCHES.)

Specimen.	Diameter: inches.	Yield-point: tons per square inch.	Ultimate strength: tons per square inch.	Elongation: per cent.	Reduction of area: per cent.
1	0·550	17·3	27·9	42·5	65
2	0·543	17·56	28·0	42	64

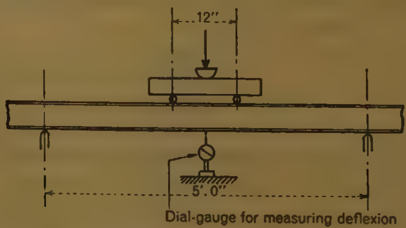
Static Test.

A static bending test was carried out on the plain girder A.4. T load–deflexion diagram from the test is shown in *Figs. 3*; the gird

Figs. 3.



Specimen Tested	Limit of proportionality: tons per square inch. On section of girder	On net section	Apparent crippling stress: tons per square inch. On section of girder	On net section at failure
① A.4. Mild-steel joist. 5″ × 3″ × 11 lb. As rolled	14·6	—	29·5	—
② A1.12. As A.4, but with rivet-holes in the tension-flange	13·3	18·9	29·0	41·1
③ B.23. " " " " butt-welded joint at mid-span	13·7	—	26·6	—
④ D.37. " " " " fillet-welded cover-plate joint at mid-span	15·9	—	31·6	—
⑤ E.56. " " " " riveted cover-plate joint at mid-span	13·7	20·8	30·5	46·0
⑥ C.26. Built-up welded girder. 5″ × 3″. No heat-treatment	11·8	—	28·0	—
⑦ C1.42 " " " " " Heat-treated at 650° C.	14·9	—	29·8	—



LOADING ARRANGEMENT.

STATIC LOAD–DEFLEXION TESTS.

Fig. 2.

FATIGUE-FRACTURE OF GIRDER A.8: TENSION-FLANGE.

FATIGUE-FRACTURE OF GIRDER A1.9: TENSION-FLANGE.

Fig. 6.

Underside of tension-flange.

Fig. 7.

Plan of tension-flange.

Fig. 8.

Fracture broken open.

ed by buckling in the compression-flange. The maximum load carried hown in *Figs. 3*, and the apparent crippling stress, calculated from the nula $f = \frac{M}{Z}$, in Table X (p. 316).

Tests of Rolled Mild-Steel Joists with Rivet-Holes in the Tension-Flange: Series A1.

Two rivet-holes, $\frac{9}{16}$ inch in diameter, were drilled through the tension-ge at mid-span, as shown in *Figs. 4*.

The second moment of area of the whole section was assumed to be 1 inch^4 units. For the determination of the maximum stress at ection through the rivet-holes, the modulus-value was calculated by t determining the new position of the neutral axis and then subtracting second moment of area of the rivet-holes from that of the whole section ut this axis. The second moment of area and the modulus of section ained were respectively 11·59 inch^4 units and 3·94 inch^3 units pectively.

igue-Tests.

The results of the tests are shown in Table III and in *Fig. 1*, p. 303 rve No. 2).

BLE III.—Fatigue-Tests on Mild-Steel Joists 5 inches by 3 inches by 11 lb., TH Two $\frac{9}{16}$-inch Diameter Rivet-Holes in the Tension-Flange. Series A1.

Specimen.	Range of stress: tons per square inch.			Remarks.
	On full section.	Calculated on section containing rivet-holes.	Number of repetitions.	
16	13·9	19·7	45,000	Broken.
9	10	14·2	285,100	Broken.
11	8	11·3	886,600	Broken.
15	6	8·5	5,216,400	Unbroken.
14	7	9·9	1,332,500	Broken.
10	6·5	9·2	2,097,300	Broken.

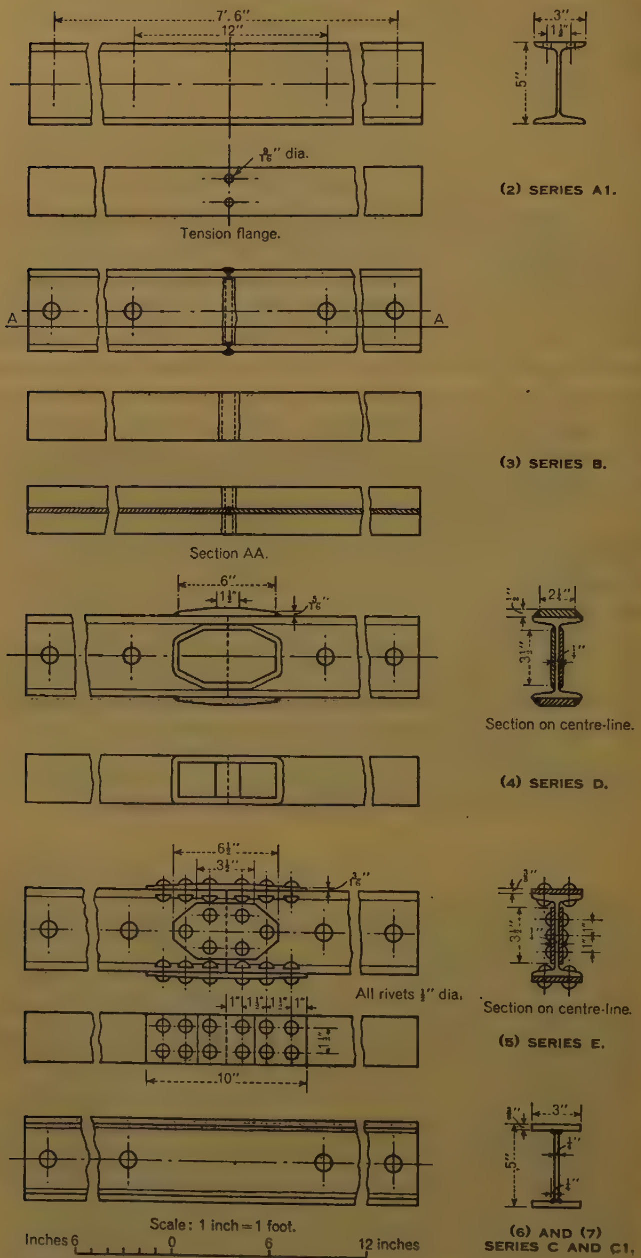
The fatigue-limit from zero minimum stress for more than 5×10^6 repetitions is tons per square inch on the section containing the rivet-holes, and 6 tons per square h on the full section.

l the fatigue-cracks are believed to have started at one of the outer undaries of the holes. *Fig. 5* shows the plan of the tension-flange of der A1.9, with the cracks proceeding from the holes.

atic Test.

A static bend-test was carried out on the girder A1.12. The maximum

Figs. 4.



SECTIONS TESTED IN GIRDER-FATIGUE TESTING-MACHINE.

d had been reached and the compression-flange had buckled before the sion-flange cracked at one of the holes. Plastic flow had also occurred r to the holes. The load–deflexion curve is shown in *Figs. 3*, p. 304. e maximum load carried is shown in *Figs. 3* and the apparent crippling ess in Table X (p. 316).

Tests of Rolled Mild-Steel Joists with a Butt-Welded Joint in the Centre: Series B and B1.

Series B.

The specimens consisted of two half-girders, 5 inches by 3 inches by lb., butt-welded together. Details of the welded joint are shown in *gs. 4.*

tigue-Tests.

Results of the tests are shown in Table IV and *Fig. 1*, p. 303 (curve . 3). The stresses quoted are maximum stresses calculated on the cross tion of the girder; the actual section through the weld is not easy to ermine. A typical fracture is shown in *Figs. 6, 7*, and *8* (facing p. 305). will be noticed (*Fig. 8*), that there is a considerable lack of penetration,

able IV.—Fatigue-Tests of Joists 5 inches by 3 inches by 11 lb., with Butt-Welded Joint. Series B. Minimum Stress Zero.

Specimen.	Range of stress: tons per square inch.	Number of repetitions.	Remarks.
8	15	24,900	Broken.
7	10	707,000	Broken.
0	8·1	2,780,400	Broken.
9	7·5	1,775,800	Broken.
4	6·5	5,377,000	Unbroken.
2	7·0	5,040,000	Broken.

The fatigue-limit from zero minimum stress for more than 5×10^6 repetitions ·5 tons per square inch.

All specimens broke through the weld except B.20, which broke partly through weld and partly at the junction of the weld and the plate.

rticularly at the root of the flange. There is little doubt that the fractures ve started at some point of the discontinuity due to this lack of pene- tion, and this probably accounts for the low result obtained of 6·5 tons r square inch from zero minimum stress. *Figs. 9* and *10* (facing p. 308) ow longitudinal sections through the flange and the web respectively.

It will be noticed that the plotted result (*Fig. 1*, p. 303) of the test of der B.20 lies above the line drawn through the other plotted points. The ack in this girder commenced at the junction of the weld and flange at e top of the flange.

The results of the tests from this series are much lower than tho obtained from tests of butt-welded plates, to which reference is made in t conclusions, the reason being the lack of penetration to which referen has already been made. The flange- and web-faces of joint B we chamfered by the workmen to a uniform depth and the two halves of t girder brought together so that there was a considerable area of conta This area is shown by the dark area of *Fig. 8* (facing p. 305) and the da line of *Fig. 9*. Weld-metal did not penetrate into these areas.

Series B1.

A further batch of 5-inch by $2\frac{1}{2}$-inch by 9-lb. joists was butt-weld and definite instructions were given as to the way in which the we was to be made. A gap was left between the vertical faces, and to all for the varying thickness of the flange the chamfer near the centre w made deeper than at the edges. Before testing, the top layer of we metal was filed flush with the flange of the joists.

Fatigue-Tests.

The results of this series of tests are shown in Table V and *Fig. 1*, p. 3 (curve No. 3*a*). It will be seen that the fatigue-range has been increas

TABLE V.—FATIGUE-TESTS OF JOISTS 5 INCHES BY $2\frac{1}{2}$ INCHES BY 9 LB., WIT BUTT-WELDED JOINT. SERIES B1. MINIMUM STRESS ZERO.

Specimen.	Range of stress: tons per square inch.	Number of repetitions.	Remarks.
B1.17 . . .	9·9	1,620,000	Broken at junction of weld a flange.
B1.18 . . .	7·9	5,174,000	Unbroken.
B1.19 . . .	9·0	5,100,000	Unbroken.
B1.20 . . .	11·5	1,037,000	Broken at junction of weld a flange.

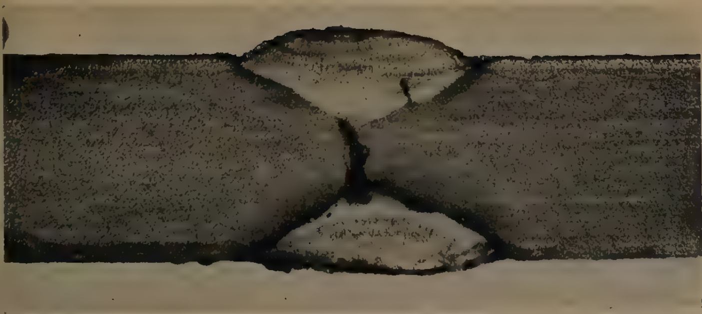
The fatigue-limit from zero minimum stress for more than 5×10^6 repetitions 9 tons per square inch.

from 6·5 to 9 tons per square inch for 5×10^6 repetitions, and from 7 to 9·6 tons per square inch for 2×10^6 repetitions. Fracture commenc in these tests at the junction of the weld and the joist near the edge of t flange.

Static Test.

A static bend-test was carried out on girder B.23. The results of t test are shown in *Figs. 3* (p. 304). In spite of the comparatively lar unwelded sectional area, there was no sign of a crack and the girder fail by buckling of the compression-flange. The static test did not indica

Fig. 9.



BUTT-WELDED JOIST: LONGITUDINAL SECTION OF FLANGE. × 3.

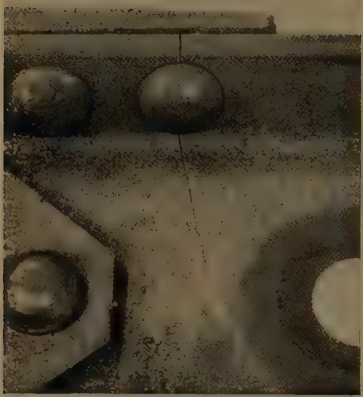
Fig. 10.

BUTT-WELDED JOIST: LONGITUDINAL SECTION OF WEB. × 3.

Fig. 11.

FATIGUE-FRACTURE OF GIRDER D.35: TENSION-FLANGE.

Fig. 12.



FATIGUE-FRACTURE OF GIRDER E.52: UNDERSIDE OF TENSION-FLANGE.

Fig. 13.

FATIGUE-FRACTURE OF GIRDER E.50: UNDERSIDE OF TENSION-FLANGE.

Fig. 14.

FATIGUE-FRACTURE OF GIRDER E.55: PLAN OF TENSION-FLANGE, WITH COVER-PLATE REMOVED.

e character of the weld. The maximum load carried is shown on *Figs. 3*, d the apparent crippling stress is shown in Table X (p. 316).

Tests of Rolled Mild-Steel Joists with a Fillet-Welded Cover-Plate Joint in the Centre: Series D.

The specimens consisted of two half-girders joined together by cover-ates fillet-welded on the flanges and on the web, as shown in *Figs. 4*, 306. The stresses quoted are maximum stresses taken on the cross ction of the girder.

tigue-Tests.

The results of the tests are shown in Table VI and *Fig. 1* (curve No. 4).

Table VI.—Fatigue-Tests of Joists 5 inches by 3 inches by 11 lb., with Fillet-Welded Cover-Plate Joint. Series D. Minimum Stress Zero.

Specimen.	Range of stress : tons per square inch.	Number of repetitions.	Remarks.
36	8	545,800	Broken.
34	6·5	1,709,400	Broken.
35	6·2	1,999,200	Broken.*
33	5·0	5,153,600	Unbroken.
32	5·5	5,264,800	Unbroken.
40	7	860,700	Broken.

The fatigue-limit from zero minimum stress for more than 5×10^6 repetitions is 5 tons per square inch.

* All specimens fractured at the junction of the tension-flange and the transverse let-weld except D.35, which broke through the centre of the cover-plate.

ll the fractures except one occurred at the junction of the transverse let-weld and flange at either end of the cover-plate. *Fig. 11* shows e one case where the fracture occurred through the centre of the cover-ate, starting in one of the longitudinal fillet welds at the junction of the o half-joists and working through the top and web cover-plates. It is f interest to note that the results show that the discontinuity occurring t the transverse fillet-weld on the flange is as serious as the discontinuity here the joist is cut.

tatic Test.

A static bend-test was carried out on girder D.37; the girder failed by uckling in the compression-flange, and there was some plastic flow at he junction of tension-flange and cover-plate. The load-deflexion curve nd the maximum load carried are shown on *Figs. 3* (p. 304) and the pparent crippling stress in Table X (p. 316).

Tests of Rolled Mild-Steel Joists with a Riveted Cover-Plate Joint in the Centre: Series E.

The specimens consisted of two half-girders joined together by cove[r]-plates riveted on the flanges and on the web as shown in *Figs. 4*, p. 30[0]. A pneumatic riveting-hammer and hot rivets were used.

Fatigue-Tests.

Results of the tests are shown in *Fig. 1*, p. 303 (curve No. 5) an[d] Table VII. All the fractures occurred at the end rivet-holes, starting a[t]

Table VII.—Fatigue-Tests of Joists 5 inches by 3 inches by 11 lb., with Riveted Cover-Plate Joint. Series E.

Specimen.	Range of stress: tons per square inch.		Number of repetitions.	Remarks.
	On full section.	On section through the end rivets.		
E.51	7·8	11	6,775,600	Unbroken.
E.52	9·9	14	339,500	Broken.
E.50	7·8	11	3,130,900	Broken.
E.55	8·8	12·5	1,354,900	Broken.
E.53	8·35	11·75	3,019,200	Broken.

All fractures occurred at the section through the end rivet-holes.
The fatigue-limit from zero minimum stress for more than 5 × 10[6] repetitions 10·75 tons per square inch on the section through the end rivet-holes, and 7·6 to[ns] per square inch on the full section.

the outer boundaries of the holes in the same way as the drilled joist series A1. A typical fracture is shown in *Fig. 12* (facing p. 309).

The fatigue-limit on a section through these holes was found to b[e] 10·75 tons per square inch, and the value obtained for the drilled jois[ts] was 8·5 tons per square inch, so that the riveting of the cover-plate ha[s] raised the fatigue-strength of the joists from 8·5 to 10·75 tons per squa[re] inch; that is, by 26·5 per cent.

There appears to be no doubt that this increase in fatigue-streng[th] is due to the friction and pressure between the cover-plate and the flang[e], these being clamped together by the rivets. *Fig. 13* (facing p. 309) sho[ws] the fracture of girder E.50, where the grip of the rivet was such that t[he] fatigue-crack had spread through the rivet-head. *Fig. 14* (facing p. 30[9]) shows half the cover-plate and rivets removed from the fracture of gird[er] E.55. The marks on the surface of the flange thus exposed are furth[er] evidence of considerable pressure between the cover-plate and the flang[e].

These results agree closely with those obtained by one of the Autho[rs]

m small riveted joints tested in tension.[1] The following is quoted from . 109 *et seq.* of the Paper referred to :—

" The differences in the results obtained from the various joints . . . l not appear, therefore, to depend on the differences of bearing stress, t rather depended upon the tightness with which the cover-plates were eted to the specimen. It was therefore thought desirable to test a joint ilar to joint R "—shown in *Figs. 12*, p. 110 of that Paper—" but with lts inserted instead of rivets. The holes in the plates were very carefully illed and the bolts made a good fit in the holes. The heads of the bolts re slotted to take a screwdriver. The joints were apparently reasonably ht, but, as will be seen, there could not be any considerable pressure tween the cover-plates and the plates under test. . . . The safe range stress from zero minimum stress is about 9 tons per square inch. The me joint, riveted, gave a safe range of stress at zero minimum stress of out 11·5 tons per square inch."

The clamping of the cover-plates in this case has raised the fatigue-mit from 9 to 11·5 tons per square inch, which is an increase of 27·8 per nt. and compares well with the results obtained on the joists.

atic Test.

A static bend-test was carried out on girder E.56 ; there was some idence of buckling of the compression-flange, but the girder finally iled by fracturing through the end rivet-holes. The riveted joint in the ort length subjected to maximum bending moment had very considerably creased the resistance to buckling. The load–deflexion curve and the aximum load carried are shown on *Figs. 3* (p. 304) and the apparent ippling stress in Table X (p. 316).

Tests on Welded Girders: Series C.

Tests were made on girders, *Figs. 4* (p. 306), made by fillet-welding the eb-plate to the flange-plates.

No heat-treatment was given after welding. The flange-plates were cked to the web-plate with a series of tacks approximately 2 inches long nd were finally welded with a fillet-weld.

etermination of Section-Modulus.

After each test the size of the specimen at fracture was ascertained by easurement with micrometer-gauges. In the case of unbroken specimens he minimum section was measured ; $\frac{1}{4}$-inch 45-degree fillet-welds were ssumed, and the second moment of area and the section-modulus were alculated by dividing the section into geometric figures.

[1] Footnote 2, p. 301.

Fatigue-Tests.

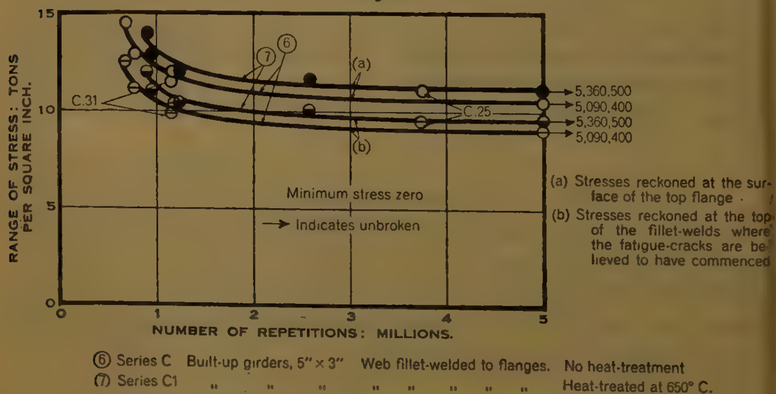
Results of the tests are shown in Table VIII and in *Fig. 15* (curv Nos. 6*a* and 6*b*). All the failures occurred in the length subjected t

TABLE VIII.—FATIGUE-TESTS ON WELDED JOISTS. SERIES C. NO HEAT-TREATMEN

Specimen.	Second moment of area: inch^4 units.	Range of stress: tons per square inch. At top surface of girder.	Range of stress: tons per square inch. At junction of fillet and flange.	Number of repetitions.	Remarks.
C.29 . .	14·16	14·5	12·6	695,300	Broken, slight creep.
C.30 . .	14·08	12·9	11·2	783,200	No creep, broken ov one of the loadi points.
C.25 . .	14·02	11·1	9·6	3,756,500	Broken, no creep; scal inclusion at fractur
C.32 . .	14·16	10·4	9·0	5,090,400	Unbroken, no creep.
C.31 . .	14·03	11·4	9·9	1,159,000	Broken, no creep; blow hole at fracture.
C.28 . .	13·95	12·0	10·4	1,195,900	Broken, no creep.

The fatigue-limit, reckoned at the surface of the top flange, from zero minimum stress for more than 5×10^6 repetitions is 10·5 tons per square inch. The corre sponding fatigue-limit at the top of the fillet-weld where the crack is believed to hav commenced is 9·0 tons per square inch.

Fig. 15.

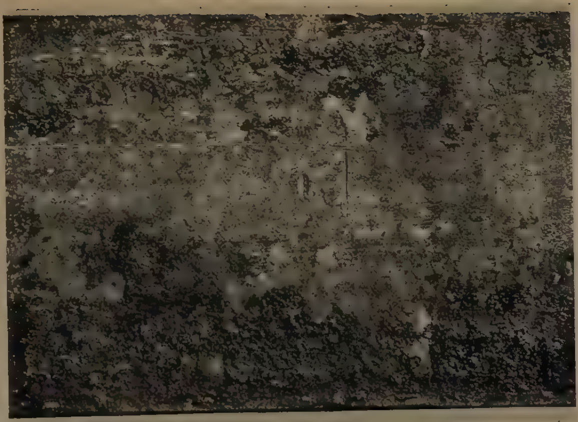


FATIGUE-TESTS IN GIRDER-FATIGUE TESTING-MACHINE.

constant bending moment; *Figs. 16* and *17* show the fracture at an earl stage of girder C.29.

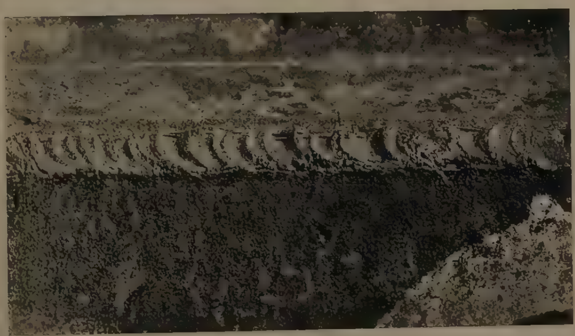
The crack is more open underneath the tension-flange than on top o the flange, suggesting that the crack started in the fillet-weld and pro ceeded through the flange. *Fig. 18* shows the fracture of girder C.3 after being broken open for inspection; the fatigue-crack had spread a

Fig. 16.



FATIGUE-FRACTURE OF GIRDER C.29: TENSION-FLANGE.

Fig. 17.



FATIGUE-FRACTURE OF GIRDER C.29: UNDERSIDE OF TENSION-FLANGE.

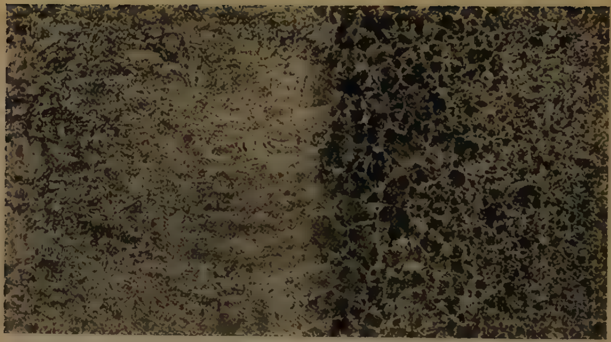
Fig. 18.

FATIGUE-FRACTURE OF GIRDER C.30: FRACTURE BROKEN OPEN.

5175.

Fig. 19.

Weld. Plate.

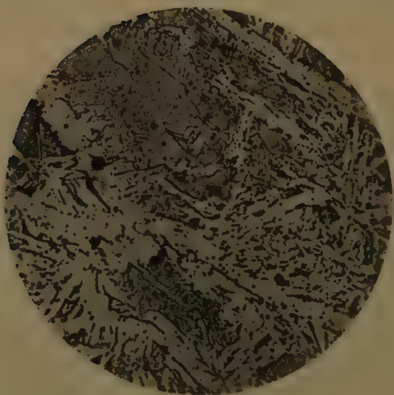


Typical junction of weld and plate. × 40.

Fig. 20.

Junction of web and plate. × 2.

Fig. 21.



Typical micro-structure of weld-metal. × 320.

WELDED GIRDER C.29.

as AA. There seems no doubt that the fracture started at the fillet-d.

The fracture of girder C.25 showed a small scale-inclusion in one of the t-welds. This specimen broke at 3,756,000 repetitions. The plotted nt is not inconsistent with the other plotted points, which suggests t this type of discontinuity is not more harmful than those less obvious continuities at which fracture of the remaining specimens commenced.

Specimen C.31 fractured at the junction of a tack-weld and the final run, ere some scale had been included, with a consequent blow-hole. The tted point for girder C.31 (*Fig. 15*, p. 312) is slightly below the general ve.

The limiting fatigue-stress of 10·5 tons per square inch calculated at outer face of the girder corresponds to a stress of 9·0 tons per square h at the top of the fillet-welds.

gin of Fracture.

From the examination of the fractures it seemed clear that the crack did t start from the extreme fibre of the tension-flange where there is maxim stress. In *Fig. 18* (facing p. 312) can be seen a light-coloured band losing the fillet-weld. This band, *Fig. 19*, is a zone of heat-affected rent-metal. Radiating from this band in all fractures there is an area of rker-coloured material (*Fig. 18*) than the rest of the fracture, which ually indicates the development of a fatigue-crack. The most probable int for the start of the fracture is therefore somewhere in the junction of ld-metal to plate.

amination of Welded Joist C.29.

A section of this joist was polished and etched with copper ammonium loride. The result is shown in *Fig. 20* under a magnification of 2. It ll be seen that the penetration is good. *Fig. 21* shows a typical photocrograph of the weld-metal at a magnification of 320, and *Fig. 19* * shows typical junction of the weld and plate under a magnification of 40. ere is no evidence of nitrogen in the weld, and the general structure is od. The black spots, *Fig. 21*, are thought to be particles of oxide of nganese. The large crystalline appearance at the junction of the weld d plate, *Fig. 19*, is due to the parent metal being heated to a high mperature during welding.

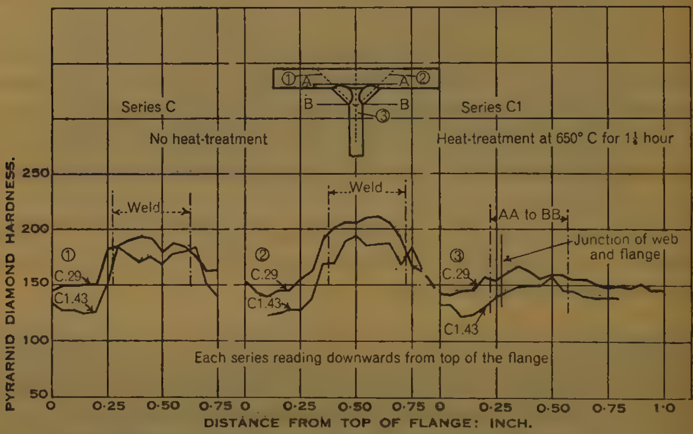
ardness of Welded Joist C.29.

Fig. 22 (p. 314) shows a series of hardness-tests which were taken on a ction cut from girder C.29. It is evident from curves Nos. 1 and 2 that the ld-metal is harder than the plate. It would appear from the hardness-

* The Authors are indebted to the Metallurgical Department of the University of effield for the preparation of *Figs. 19* and *21*.

distribution curve from fillet No. 1 that the second fillet to be weld (curve No. 2) had an annealing effect on fillet No. 1.

Fig. 22.



HARDNESS-VALUES ON WELDED JOISTS C.29 AND C1.43.

FATIGUE-TESTS ON WELDED GIRDERS AFTER HEAT-TREATMENT AT A TEMPERATURE OF 650° C. (STRESS-RELIEVED): SERIES C1.

Details of Stress-Relieving.

The girders were welded similarly to series C (group 6). After weldin the joists were placed in reheating furnaces at a temperature of 460° C. the temperature was raised to 600° C. in a period of 1 hour, and was the maintained at an average temperature of 650° C. for about 20 minute The joists were then removed and cooled in air.

Determination of Section-Modulus.

Measurements of the section were taken with a micrometer-gauge an the section-modulus was obtained as for the welded joists (series C).

Fatigue-Tests.

The results of the fatigue-tests are shown in Table IX and *Fig. 1* p. 312 (curves Nos. 7*a* and 7*b*). All failures except one occurred betwee the loading-points in the length subjected to constant bending momen There appears to be no essential difference between the fractures of the girders and those of series C. The light-coloured band enclosing th fillet-weld and the dark-coloured areas radiating from it were identic with those of the non-heat-treated welded joists. It may therefore b reasonably assumed that the fatigue-crack originated in the same mann for both types of welded girders.

TABLE IX.—FATIGUE-TESTS ON WELDED JOISTS. SERIES C1. STRESS-RELIEVED AT 650° C.

Specimen.	Second moment of area : inch^4 units.	Range of stress : tons per square inch.		Number of repetitions.	Remarks.
		At top surface of girder.	At junction of fillet and flange.		
43 . .	14·07	11·9	10·4	1,250,500	Broken, no creep.
48 . .	14·01	11·0	9·6	5,260,500	Unbroken, no creep.
47 . .	13·87	11·6	10·1	2,593,900	Broken, no creep.
45 . .	13·95	12·8	11·1	958,300	Broken $\frac{5}{8}$ inch outside the constant-bending length, no creep.
44 . .	14·05	14·0	12·2	917,700	Slight initial creep, broken.

The fatigue-limit, reckoned at the surface of the top flange, from zero minimum stress for more than 5 × 10^6 repetitions is 11 tons per square inch. The corresponding fatigue-limit at the top of the fillet-weld where the crack is believed to have commenced is 9·6 tons per square inch.

Hardness of Welded Girder C1.43.

A series of hardness-tests were taken on a half-section cut from girder C1.43; these are shown in *Fig. 22.*

Static Tests of Welded Girders.

Static bend tests were carried out on girder C1.42 (stress-relieved) and on girder C.26 (no heat-treatment). Failure occurred in both cases by buckling of the compression-flange. There was no evidence of failure of the fillet-welds.

It is interesting to note that, although the stress-relieving of the welded joists has raised the limit of proportionality on first loading from 11·8 to 14·9 tons per square inch (that is, by 25 per cent.), the fatigue-limit has only been raised from 10·5 to 11 tons per square inch (that is, by 5 per cent.). Further, the apparent crippling stress under static loading has only been raised from 28 to 29·8 tons per square inch.

SUMMARY OF TESTS.

Table X (p. 316) summarizes the results obtained. Calling the fatigue-range of the plain joist unity, the fatigue-range factors, obtained by dividing the fatigue-range for any joint from zero stress by the fatigue-range of the plain joists, are shown in the Table. It will be seen that no joint gives a fatigue-range factor of more than 0·67, and in this case the real fatigue-range factor should be taken as 0·45. The fillet-welded girders gave fatigue-factors based on the stress at the fillet of 0·56 and 0·60 respectively. In a deeper girder the stress at the fillet is the all-important stress. The

TABLE X.—Table showing Fatigue-Ranges and Static Strengths of Girders.

Test specimen.	Maximum stress reckoned on:	Fatigue-limit (tension) for 5×10^6 repetitions: tons per square inch.	Fatigue-range factor.	Static strength: tons per square inch.		
				Limit of proportionality.	Apparent crippling stress.	Static-strength factor.
1. Plain joist. Series A	Original section of joist	0 to 16	1	14·6	29·5	1
2. Drilled joist. Series A1	Original section of joist	0 to 6	0·38	13·3	29·0	0·98
	Net section of joist	0 to 8·5	0·53	18·9	41·1	—
3. Butt-welded joist. Series B	Original section of joist	0 to 6·5	0·41	13·7	26·6	0·90
Butt-welded joist. Series B1	Original section of joist	0 to 9·0	0·56	—	—	—
4. Joist with fillet-welded cover-plate joint. Series D	Original section of joist	0 to 5·5	0·34	15·9	31·6	1·07
5. Joist with riveted cover-plate joint. Series E	Original section of joist	0 to 7·6	0·45	13·7	30·5	1·03
	Net section of joist	0 to 10·75	0·67	20·8	46·0	—
6. Welded girder, as welded. Series C	Maximum stress at top of flange	0 to 10·5	0·66	11·8	28·0	0·95
	Maximum stress at fillet	0 to 9·0	0·56	—	—	—
7. Welded girder, stress-relieved. Series C1	Maximum stress at top of flange	0 to 11·0	0·69	14·9	29·8	1·01
	Maximum stress at fillet	0 to 9·6	0·60	—	—	—

The load carried by the girder under either static or repeated stresses is proportional to the stress reckoned on the original section.

tt-welded joints (series B) gave very poor results. By careful attention the design of the butt-weld, however, the fatigue-factor, as shown series B1, is as high as for the fillet-welds of the welded girder. The ults from these butt-joints, series B and B1, suggest the desirability the designer defining how the joint is to be made.

Although the results from series B are low, the fatigue-range factor is her than the factor of series A1 when loads are compared or, in other rds, the stress is reckoned on the cross section of the joist away from the et-holes.

It is of interest to note from *Fig. 1* (p. 303) that for, say, 200,000 petitions, curves Nos. 2 and 5 give about the same fatigue-range. It is ggested that the fatigue-range of the riveted joint depends upon the htness of the cover plates, but curve No. 2 (*Fig. 1*) gives the safe stress which flanges with drilled holes can be subjected, and is the safe stress assume for riveted joints. It is desirable also to point out that cracks veloped in the fillet-welds transverse to the flanges of the joists of series D stresses less than those in the fillet-welds of the welded girders. In the rmer case there is a more rapid discontinuity, which probably accounts for e lower result.

It will be clearly seen from Table X that, from the point of view of peated stresses, static tests are of little value.

Comparison of Results with those of Other Tests.

In this conclusion, it is relevant to compare the results given with ose obtained by one of the Authors, some of which are published sewhere,[1] and with those obtained by other workers.

These have been embodied in *Figs. 23* and *24* (p. 321), in which the inimum stress is plotted as abscissa and the range of stress as ordinate. he source of the experiments, particulars of the type of test, and the tigue-limit obtained are given in Tables XI and XII (pp. 318–320). The raight lines are drawn on *Figs. 23* and *24* to indicate the safe range of stress r particular types of specimens. The ordinate to the straight line AB gives smaller range of stress for varying minimum stresses than would be obtained r a steel giving a range of $\pm$ 15 tons per square inch at zero mean stress. he curve abcd was obtained from thin black plates.[2] Points e and f were btained from turned specimens of a steel having a tensile strength of 2 tons per square inch. Numbers 30 were obtained from 3-inch by 3-ch bars at zero and at 5 tons per square inch minimum stress respectively. umbers 11 were obtained from butt-welded stress-relieved unmachined lates. Points 31 were obtained by Professor B. P. Haigh from repeated

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[1] Second Report of Welding Research Committee. Proc. Inst. Mech. E., vol. 133 936), p. 5.

[2] Footnote 2, p. 301.

TABLE XI.—REFERENCE FOR NUMBERS OF *Fig. 23* (p. 321).

No.	Description of specimens.	Number of repetitions on which fatigue-ranges are based.	Fatigue-limit: tons per square inch.	Investigators.
1	Boiler-plate	10^7	±15·2	Lea and Parker.
2	"P" weld. G3 plate. Normalized, machined all over	10^7	±10·6	,, ,, ,,
3	,, ,, ,, machined flush	10^7	± 9·8	,, ,, ,,
4	,, ,, ,, unmachined	10^7	± 8·9	,, ,, ,,
5	,, ,, Annealed, machined all over	10^7	±10·0	,, ,, ,,
6	,, ,, ,, unmachined	10^7	± 8·5	,, ,, ,,
7	,, ,, As welded, machined all over	10^7	±11·3	,, ,, ,,
8	,, ,, ,, unmachined	10^7	± 8·1	,, ,, ,,
9	"P" weld. G2 plate. Normalized, machined flush	10^7	± 9·8	,, ,, ,,
10	,, ,, ,, unmachined	10^7	± 9·1	,, ,, ,,
11	,, ,, Annealed, unmachined	10^7	± 8·5	,, ,, ,,
12	,, ,, As welded, unmachined	10^7	± 8·1	,, ,, ,,
13	"W" weld. G2 plate. Normalized, machined all over	10^7	±12·5	,, ,, ,,
14	,, ,, Annealed, ,, ,, ...	10^7	±13·5	,, ,, ,,
15	,, ,, As welded, ,, ,, ...	10^7	±10·5	,, ,, ,,
16	"U" weld. G2 plate. Normalized, ,, ,, ...	10^7	± 8·5	,, ,, ,,
17	Mild-steel joists, 5 inches by $2\frac{1}{2}$ inches by 9 lb. As rolled	10^7	0 to 14·75	Lea and Whitman.
18	,, ,, ,, ,, $\frac{3}{8}$-inch diameter rivet-holes in the flanges. (Stresses on net section.)	10^7	0 to 10	,, ,, ,,

19	"Chromador" steel joists, 5 inches by $2\frac{1}{2}$ inches by 9 lb. As rolled	10^7	0 to 15·5	Lea and Whitman.
20	,, ,, ,, ,, $\frac{3}{8}$-inch diameter rivet-holes in the flanges. (Stresses on net section)	10^7	0 to 13	,, ,, ,,
21	Mild-steel joists, 5 inches by 3 inches by 11 lb. As rolled	$7 \cdot 5 \times 10^6$	0 to 16	,, ,, ,,
22	,, ,, ,, ,, $\frac{9}{16}$-inch diameter rivet-holes in the tension-flange. (Stresses on net section)	5×10^6	0 to 8·5	,, ,, ,,
23	Mild-steel joists, 5 inches by 3 inches by 11 lb. With riveted cover-plate joint. (Stresses on net section)	5×10^6	0 to 10·75	,, ,, ,,
24	Mild-steel joists, 5 inches by $2\frac{1}{2}$ inches by 9 lb. With butt-welded joint	5×10^6	0 to 9·0	,, ,, ,,
25	,, ,, ,, ,, No penetration at root of flange	5×10^6	0 to 5·5	,, ,, ,,
26	,, ,, 5 inches by 3 inches by 11 lb. No penetration at root of flange	5×10^6	0 to 6·5	,, ,, ,,
27	,, ,, ,, ,, With fillet-welded cover-plate joint	5×10^6	0 to 5·5	,, ,, ,,
28	Built-up welded girders, 5 inches by 3 inches. No heat-treatment. } Stress reckoned at fillet-welds.	5×10^6	0 to 9·0	,, ,, ,,
29	,, ,, ,, ,, Heat-treated at 650° C. } Stress reckoned at fillet-welds.	5×10^6	0 to 9·6	,, ,, ,,
30	3-inch by 3-inch bars with butt-welded joint	5×10^6	0 to 11	,, ,, ,,
31	Plate-specimens with butt-weld containing slag-inclusions and blow-holes	10^7	0 to 9	Haigh.

Specimens 1 to 16 were tested in the constant-bending-moment machine, and specimens 17 to 30 were tested in the girder-testing machine. Specimens 31 were tested in the Haigh machine and the results are published in the Symposium on the Welding of Iron and Steel (The Iron and Steel Institute, 1935), vol. 2, p. 795.

TABLE XII.—REFERENCE FOR NUMBERS OF *Fig. 24.*

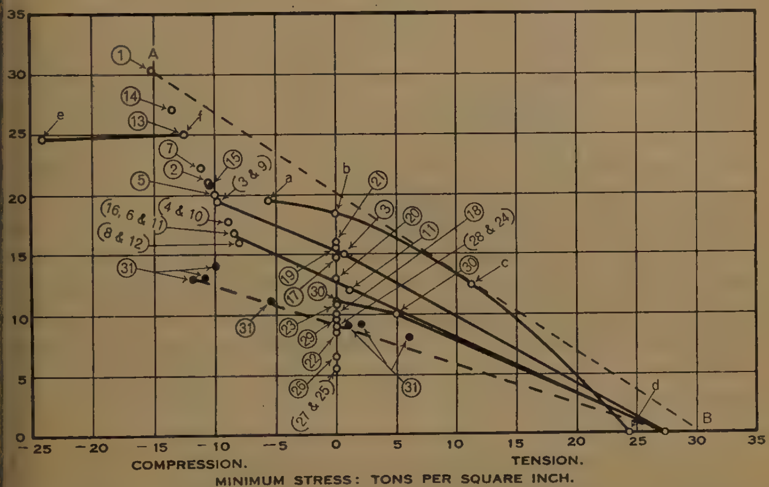
No.	Descriptions of specimens.	Number of repetitions on which fatigue-ranges are based.	Fatigue-limit: tons per square inch.	Investigators.
1	Plate-specimens with hole	2×10^6	0 to 9·8	Graf.
2	,, ,, different riveted joints	2×10^6	0 to 9·5–12	Graf, Memmler, Bierett and Gehler.
3	Butt-welded plate-specimens with root unsealed	2×10^6	0 to 8·3	Graf and Bierett.
4	,, ,, ,, sealed	2×10^6	0 to 11·4	Graf, Memmler, and Bierett.
5	,, ,, ,, ,, machined	2×10^6	0 to 15·2	Graf.
6	Diagonal butt-welded plate-specimens, root-sealed, not machined	2×10^6	0 to 14·0	,,
7	Transverse fillet-welded cover-plate joints for plate-specimens. Ordinary welds	2×10^6	0 to 5·3	,,
8	Similar specimens, light welds, smooth flow, no undercut	2×10^6	0 to 6·5	,,
9	Longitudinal fillet-welded cover-plate joints for plate-specimens. Ordinary welds	2×10^6	0 to 5·1–5·7	,,
10	Similar specimens, ground or machined hollow welds	2×10^6	0 to 7·0–7·6	,,
11	Rolled steel joists, 12 inches deep with riveted cover-plate joint	2×10^6	0·635 to 8·9	,,
12	,, ,, ,, ,, ,, ,, butt-welded joint	2×10^6	0·635 to 10·2	,,
13	,, ,, ,, ,, ,, ,, diagonal butt-welded joint	2×10^6	0·635 to 11·4	,,
14	,, ,, ,, ,, ,, ,, butt-welds, with different cover-straps	2×10^6	0·635 to 7·0–11·4	,,
15	Built-up welded girder	2×10^6	7·2 to 13·9	Diepschlag, Matting, Oldenburg and Kater.

Specimens 1 to 10 give fatigue-values from which the German working stresses are derived. They are based on tests under direct stresses carried out in the Amsler pulsator and the "vibrating bridge."

Specimens 11 to 14 were tested in bending in a specially-adapted hydraulic pulsator, and have been published in *Die Bautechnik*, vol. 15 (*Der Stahlbau*, vol. 10 (1937), p. 9). The tensile strength of the steel was 23·5 tons per square inch. (St. 37.)

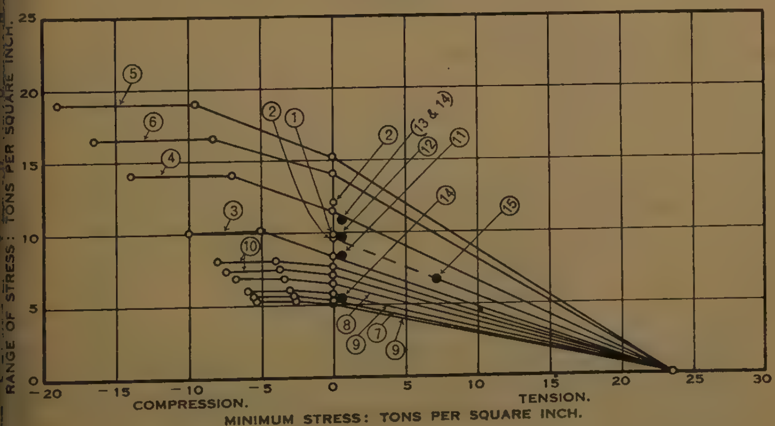
ect-stress tests of machined welds which contained slag-inclusions and w-holes. Very few welds are completely free from such defects.

Fig. 23.



umber 27 is for the fillet-welded cover-plate joint. Numbers 25 and 26 e for the butt-joints of joists with no penetration at the root of the nge.

Fig. 24.



The Building Research Station of the Department of Scientific and dustrial Research has prepared an abstract from direct-stress fatigue-sts carried out in Germany. Fatigue-values based on these tests, from hich the working stresses in the German code of practice are derived,

are shown in Table XII and are plotted in *Fig. 24*. More recently Professor Otto Graf,[1] using a machine with four-point loading which in principle is the same as the Sheffield machine,[2] has obtained the results shown in Table XIII and *Fig. 24*. The tests in Germany and in Sheffield were carried out quite independently and without any knowledge of each other's work. Point number 11, *Fig. 24*, is from a girder with a riveted joint. The range obtained for 2,000,000 repetitions is 8·2 tons per square inch from 0·635 ton per square inch minimum stress. At Sheffield for a rolled joist with holes in the tension-flange (No. 22, *Fig. 23*), the range for 5,000,000 repetitions was 8·5 tons per square inch and for 2,000,000 repetitions it was 9·1 tons per square inch.

In designing girders, the Authors suggest that the diagrams to the right of the zero ordinate are those from which the safe range of stress can be assumed. From *Figs. 23* and *24*, it will be seen that for transverse fillet welds the safe range of stress from zero minimum stress is very little greater than 5 tons per square inch. For the worst butt-joint tested the range is about the same. For well-made properly-designed butt-joints the range from zero minimum stress is from 9 tons per square inch obtained from joists, to 15 tons per square inch obtained from thin plates.

Table XIII gives more detailed information of the tests carried out by

TABLE XIII.—FATIGUE-TESTS BY PROFESSOR OTTO GRAF (*see Figs. 25*).

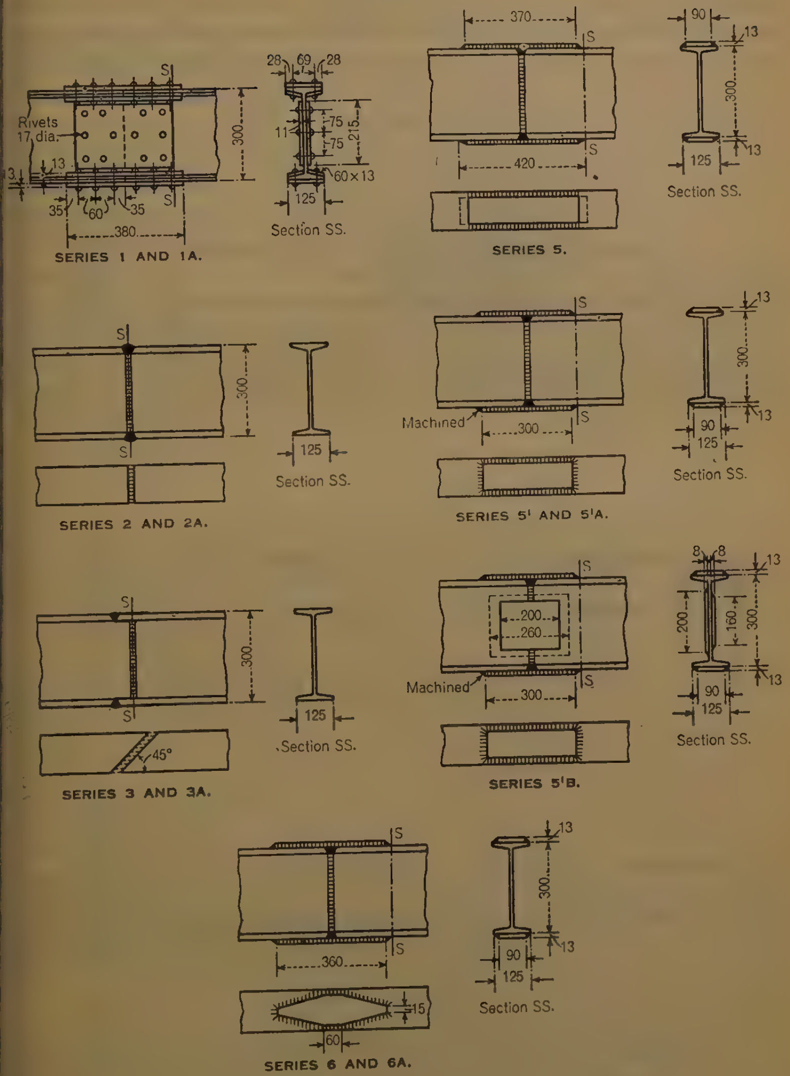
Series.	Fatigue bending strength for 2,000,000 repetitions at 1 kilogram per square millimetre minimum stress : tons per square inch.	
	Pure bending.	Bending and shear.
1 and 1*a*	8·9 (8·3)	8·8 (8·3)
2 and 2*a*	10·2 (9·5)	9·5 (8·9)
3 and 3*a*	11·4 (10·8)	—
5	7·6 (7·0)	—
5′ and 5′*a*	11·4 (10·8)	11·4 (10·8)
5′*b*	—	11·4 (10·8)
6 and 6*a*	7·0 (6·4)	7·0 (6·4)

The fatigue bending strengths given in this Table are the maximum stresses from 0·635 ton per square inch minimum given by Professor Graf for 2 × 10^6 repetitions. The figures given in the brackets are the ranges of stress from 0·635 ton per square inch minimum. The values given in col. (2) of Table XIV (p. 325), are interpolated values by the Authors for zero minimum stress.

[1] "Versuche über das Verhalten von genieteken und geschweissten Stössen in Trägern I 30 aus St 37 bei oftmals wiederholter Belastung." *Die Bautechnik*, vol. 15 (*Der Stahlbau*, vol. 10 (1937), p. 9.)

[2] Footnote 3, p. 301.

Figs. 25.



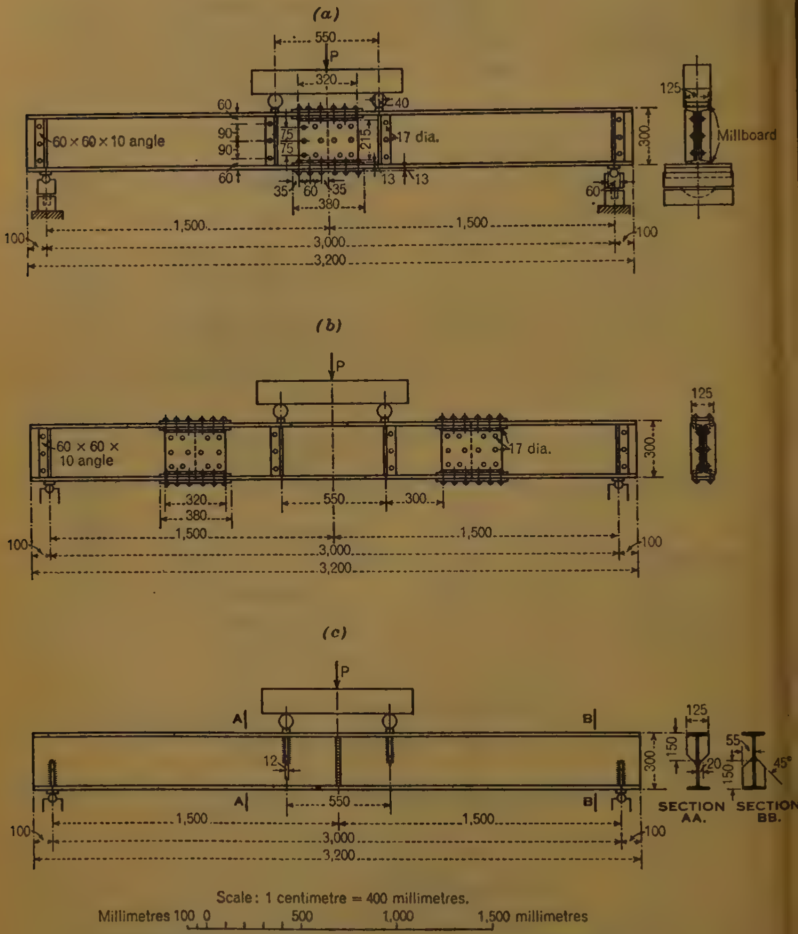
NOTE: All dimensions are in millimetres.

Scale: 1 centimetre = 250 millimetres.
Millimetres 100 0 100 200 300 400 millimetres

JOINTS TESTED BY PROFESSOR OTTO GRAF (*see* Table XIII).

Professor Graf on rolled steel joists. The specimens tested, *Figs. 26*, wer
approximately 12 inches deep and 10 feet span. They were subjected t
repeated bending under four-point loading. Joints could be subjected t
pure bending or combined bending and shear by placing them inside o

Figs. 26.



FATIGUE-SPECIMENS USED BY PROFESSOR OTTO GRAF.

outside the length of constant bending (*Figs. 26*), as contemplated for th
Sheffield machine. The machine used by Professor Graf was a speciall
adapted hydraulic pulsator working at from 160 to 210 repetitions pe
minute. Load was applied directly on to the compression-flange, a
shown in *Figs. 26*; an initial load was applied corresponding to a minimu

r dead-load stress of 1 kilogram per square millimetre (namely, 0·635 ton per square inch). In Table XIII (p. 322) are given the limiting maximum stresses obtained with this minimum stress for more than 2×10^6 repetitions, and also the ranges of stress.

For the butt-welded girders of series 2 (Table XIII), the safe limiting range of stress from 1 kilogram per square millimetre (0·635 ton per square inch) minimum stress was 15 kilograms per square millimetre (9·5 tons per square inch) for 2×10^6 repetitions. The corresponding maximum limiting stress is therefore 16 kilograms per square millimetre, or 10·2 tons per square inch. Both values are given in Table XIII.

In *Fig. 24*, p. 321, these limiting ranges of stress are plotted at a minimum stress of 0·635 ton per square inch. The intersections with the zero ordinate of the straight lines passing through these points and the tensile strength of the material gives the approximate fatigue bending-strengths from zero minimum stress. These values are given in Table XIV and are compared with the results obtained by the Authors for 2×10^6 repetitions of stress. In *Fig. 1* (p. 303) the Authors have obtained the fatigue-range for 5×10^6 repetitions. It will be noticed that the difference between Professor Graf's figures given in Tables XIII (those unbracketed) and XIV varies between 0·3 and 0·4 ton per square inch (that is, about 0·5 kilogram per square millimetre).

TABLE XIV.—BENDING FATIGUE-TESTS ON JOINTED I-SECTION JOISTS.

Type of joint.	Results given from zero minimum stress for more than 2×10^6 repetitions: tons per square inch.	
	Sheffield results.	German results.† (Interpolated.)
Joist with drilled tension-flange . . .	9·1	—
Riveted joint	12·2	8·5
Diagonal butt-weld	—	11·1
Butt-weld (good penetration)	9·6	9·8
Butt-weld (bad penetration at root of flange)	7·3 and 7·0 *	—
Fillet-welded cover-plate joint	6·3	—
Butt-welded joint with different cover-straps fillet-welded	—	6·6 to 11·1 §

* Journal Inst. C.E., vol. 7 (1937–38), p. 119 (November, 1937).
† The values given in this Table are interpolated from Table XIII.
§ The fillet-welds giving this high value had been milled.

It is of interest to note (Table XIII) that cover-straps do not improve the fatigue-resisting properties of good butt-welds, and can be deleterious. Such plates, however, will improve the fatigue-strength of butt-welds when the fillet-welds are machined to give even contours.

Professor Graf [1] has also tested a 10-inch welded I-section beam unde four-point loading repeated bending, with a butt-welded joint at the centre The tension-flange of this beam had an additional welded plate. With stresses varying in the tension-flange from 0·4 to 9·8 tons per square inch and in the compression-flange from 0·6 to 16·5 tons per square inch, on beam failed in the tension-flange after $1{\cdot}6 \times 10^6$ repetitions and the othe did not fail after $2{\cdot}1 \times 10^6$ repetitions. These results are in close agree ment with his later results on butt-welded rolled-steel joists, and also wit the results obtained at Sheffield. These two tests also confirm many othe tests that butt-welds have a higher value in compression-fatigue than i tension-fatigue.

There have been few fatigue-tests carried out on built-up welded girder similar to those described in this Paper. Messrs. Hans Bühler and Herber Buchholtz [2] have tested such beams in bending fatigue and have found as have the Authors, that fractures started at the fillet-welds, that is, a the less highly-stressed side of the tension-flange. By the use of profil flange-plates welded to the web by butt-welds they increased the bending strength by 28 per cent.

In the Paper it is shown that stress-relieving the fillet-welds ha increased the fatigue-limit for 5×10^6 repetitions from 10·5 to 11 tons pe square inch ; such stress-relieving is not recommended by Professor Graf,[3] but Mr. W. Schick [4] has shown that it is possible to raise the fatigue strength of fillet-welds by 10 per cent. but not the fatigue-strength of butt welds. Messrs. F. C. Lea and C. F. Parker have shown that stress-relievin may increase the fatigue-range of butt-welds in ½-inch plate. In on series of tests the fatigue-range for machined specimens was raised by th heat-treatment from ± 10·4 tons per square inch to ± 13·5 tons pe square inch. In other series of tests the stress-relieved unmachine specimens also gave a fatigue-range a little greater than the " as-welded " specimens.

Comparing welds in low-alloy steel, St. 52, with mild-steel welds, St. 37 Messrs. E. Diepschlag, A. Matting and G. Oldenburg,[5] and Mr. J. Kater [6] obtained the fatigue-value for both these metals in the form of unstiffene I-section beams. For St. 52 steel they obtained a range of 9·3 tons pe square inch from a minimum stress of 7·2 tons per square inch, and fo St. 37 a range of 6·7 tons per square inch for a minimum stress of 7·2 ton

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[1] " Dauerbiegeversuche mit geschweissten Trägern I 30 aus St 37." *Die Bautechni* vol. 14 (*Der Stahlbau*, vol. 9 (1936), p. 71).

[2] " Belastungs-Dehnungs-Messungen an I-Trägern mit und ohne Aussteifung." *Die Bautechnik*, vol. 13 (*Der Stahlbau*, vol. 8 (1937), p. 50).

[3] " Dauerfestigkeitsversuche mit Schweissverbindungen," pp. 18–27. Berlin 1935.

[4] *Techn. Mitt. Krupp*, vol. 2 (1934), p. 43.

[5] *Archiv für Eisenhüttenwesen*, vol. 9 (1935–36), p. 341.

[6] " Pulsator Tests of I beams." *Poly. Weekblad*, vol. 27 (1933), pp. 385 and 405

er square inch. The extreme fibre-stresses are quoted. By plotting the sult obtained for the mild-steel welded girders in *Fig. 24* (point 15) the nge from zero minimum stress is seen to be approximately equivalent 9·5 tons per square inch.

Although no definite specifications are given for electrodes, the German vestigators in their Report to the *Verein deutscher Ingenieure* [1] make the llowing recommendations for welds that will be subjected to repeated resses :—

(1) The surface of weld-beads should be smooth and the transition from parent-metal should be gentle and without holes.
(2) The weld-metal should be as free from pores and slag-inclusions as possible, and should show good penetration all round.
(3) Arc-welds should be made with as few interruptions as possible.
(4) The weld-metal should be as ductile as possible.

These recommendations confirm the experience of the Authors. uctility, however, has apparently no definite relationship with the tigue-behaviour of a sound weld, but it is important from other points f view.

It will be seen that the results obtained at Sheffield agree with those btained in Germany. It is worth mentioning that the German experi-ents and machines were made possible by the co-operation of Government epartments, large steel firms and the State railways. The machine esigned and constructed at Sheffield 5 years ago was made with very mited resources, and only the devotion of University assistants and echanics made it possible.

The specimens have been supplied by two steel firms. The first series f experiments were carried out with the assistance of a research student olding a university scholarship. The later work has been done with the elp of the Department of Scientific and Industrial Research and the esearch Committee of The Institution of Civil Engineers. The Author esponsible for the design and construction made the machine as large s his resources admitted, and he is of the opinion that it is large enough to ake most of the necessary fundamental investigations.

Much further work is, however, required, and it seems now necessary o consider the design of a larger machine. It is hoped that the industry will make this possible.

The thanks of the Authors are due to the Department of Scientific and Industrial Research and to The Institution of Civil Engineers for financial assistance, and to the University of Sheffield for facilities to carry out the research.

The Paper is accompanied by seven sheets of drawings and nineteen

[1] Footnote (3), p. 326.

photographs, from some of which the Figures in the text and the thre[e] half-tone page-plates have been prepared, and by the following Appendi[x].

APPENDIX.

Welding Details.

No. 10G electrodes were used with a current of from 120 to 130 amperes. The electro[de] was a heavily-coated (extruded) rod :

Typical test-results for all welded specimens were as follows :

Ultimate tensile strength	31·9 tons per square inch.
,, yield-point	25·6 ,, ,,
Elongation on 3·54 diameters	28·0 per cent.
Elongation on 8 diameters	19·5 ,, ,,
Reduction of area	52·0 ,, ,,

Specimens used for these results were not heat-treated after welding.

Paper No. 5132.

"Fluid Flow Through Nozzles, Orifices, and Borda Mouthpieces."

By *the late* JOHN LAWRENCE HODGSON, B.Sc., Assoc. M. Inst. C.E., and GEORGE MUIRHEAD CLARK, M.A., M. Inst. C.E.

(Ordered by the Council to be published in Abstract form.)[1]

E first part of the Paper deals with the compressibility-factor, and an pression is developed which gives this factor as a convergent series of wers of h/P_1, where h denotes the observed difference of pressure across e nozzle or orifice (that is, $h = P_1 - P_2$). The expression obtained is

$$\delta^2 = \left\{1 - (3k - 2) \cdot \frac{x}{2} \pm \ . \ . \ . \right\}\left\{1 - 2k\left(\frac{1}{n^2} + \frac{1}{n^4}\right) \cdot x + \ . \ . \ . \right\},$$

here δ denotes the compressibility-factor,

k ,, ,, ratio of the specific heat at constant volume to that at constant pressure (C_v/C_p),

x ,, ,, ,, h/P_1, already defined,

n ,, ,, ,, of the area of the pipe to that of the nozzle or orifice.

This series is rapidly convergent, so that only the terms involving the st power of x need be retained and the compressibility-factor may be lculated from

$$\delta = 1 - \left\{\left(\frac{3k - 2}{4}\right) + k\left(\frac{1}{n^2} + \frac{1}{n^4}\right)\right\} \cdot x.$$

The Paper then shows that, although the factor is dependent on the lue of k, for practical purposes it is independent of variations in k, so at the same expression can be used for the flow of many other gases well as for air.

The second part of the Paper deals with the use of a Borda mouth-ece for the measurement of air-flow. Tests show that this method gives ry accurate results, and that mouthpieces may be used in place of ifices or nozzles. The rate of flow is calculated from

$$Q = 90Kd^2\sqrt{B/T}\sqrt{h},$$

[1] The MS. and drawings may be seen in the Institution Library.—SEC. INST. C.E.

where Q denotes the rate of flow in cubic feet per minute, measured as f air at a pressure of 30 inches of mercury and at a tempe ture of 60°F.,

90 is a coefficient including all conversion-factors, its error be less than 0·1 per cent.

K denotes the coefficient of discharge of the mouthpiece, its va being 0·51 over the usual working ranges,

d ,, external diameter of the mouthpiece in inches,

B ,, barometric height in inches of mercury,

T ,, atmospheric temperature in °F. abs.,

h ,, manometer-head in inches of water.

The precautions necessary to obtain accurate results are described.

The Paper is accompanied by four sheets of diagrams.

NOTE.—The Institution as a body is not responsible either for t statements made, or for the opinions expressed, in the Papers publish

ENGINEERING RESEARCH.

THE INSTITUTION RESEARCH COMMITTEE.

Joint Sub-Committee on Pile-Driving.

[S]ince January, 1936, the work on stresses in reinforced-concrete piles, [ori]ginally commenced in conjunction with the Federation of Civil Engineer[ing] Contractors and the Building Research Station, has been continued in [ass]ociation with The Institution through the Joint Sub-Committee on [Pil]e-Driving. The accounts published in the Journal [1, 2] summarized the [wo]rk to those dates, and since then the research has been concerned with [tw]o main lines :—

(1) The development of a hydraulic helmet to provide a constant type of packing which would avoid the high peak-stresses which may give dangerous conditions when the more normal packing compacts under driving ; and

(2) The development of a simple type of indicator which could be used in cases of hard driving as a warning when dangerous stresses were being approached.

The following Interim Report (pp. 332 *et seq.*) describes the work of the [Su]b-Committee under three headings :—

(1) The experimental hydraulic helmet.

(2) The peak-stress indicator.

(3) A new method for determining the stiffness-factor k/A for ordinary packing materials.

The third item is a brief note describing a new method of determining [th]e stiffness-factor required in the calculations given in the previous [ac]counts [1, 2] referred to above.

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[1] W. H. Glanville, G. Grime and W. W. Davies, "The Behaviour of Reinforced-[Co]ncrete Piles During Driving." Journal Inst. C.E., vol. 1 (1935–36), p. 150 [(D]ecember 1935.)

[2] "Notes and Practical Suggestions on Pile-Driving." *Ibid.*, vol. 2 (1935–36), [p.] 587. (April 1936.)

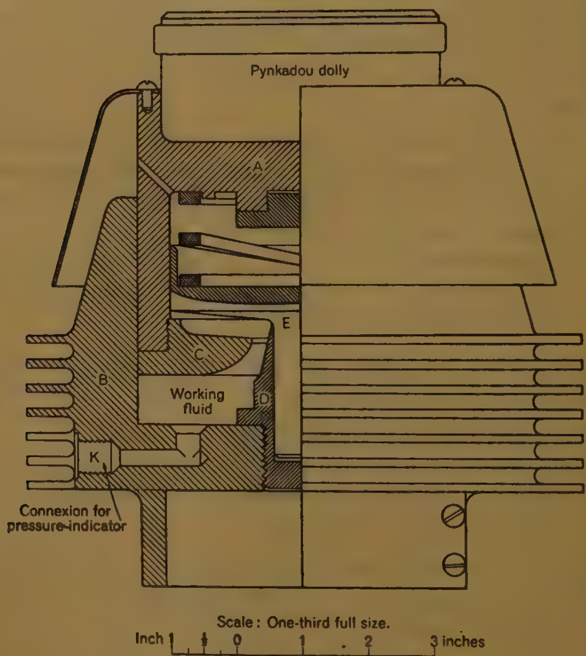
Pile-Driving. Interim Report No. 1.

Packing Materials for Pile-Driving : The Experimental Hydraulic Helmet.

Design and Construction of the Model Helmet.

The hydraulic helmet, as designed and constructed at the Buildi
Research Station, makes use of the principles of the ordinary hydrau
buffer, in which a liquid is caused to flow from one side of a piston to
other through a small orifice.

Fig. 1.



Hydraulic Helmet.

In the design it was assumed that there was no change of momentu
at impact, and that for the orifice the coefficients of contraction a
velocity were constant. Making use of these assumptions, the orif
was designed and constructed to decrease in area during a stroke of ½ in
in such a manner that the pressure under the main piston would, the
retically, remain constant during the period of the blow.

A composite elevation and sectional view of the completed helmet
shown in *Fig. 1.* It consists of a cylinder B which fits on the head of t

or impact-specimen and in which works the main piston or ram A. lower end of the piston A is partially closed by a plate C, in which is ntral circular orifice. A plug D, concentric with the hole in C, is wed into the base of the cylinder. Working inside the main piston is uxiliary piston E, and between E and A is a stiff helical spring. When piston A is depressed the fluid under it passes through the annular ce formed between C and D into the space above C. To accommodate fluid the piston E moves relative to the main piston. The plug D is haped that the area of the annular orifice gradually diminishes to zero ng the $\frac{1}{2}$-inch stroke. The spring, which is compressed by an amount al to the relative movement between A and E, forms a convenient hod of returning the system to its initial position after a blow. A rt pynkadou dolly is fitted above the main piston to receive the hammer. he tests described below a medium-grade lubricating oil was used as the king fluid.

ctical Tests on the Model Helmet.

For pile-driving tests with the model helmet a reinforced-concrete pile feet 3 inches long and 4 inches square in cross section was constructed, h piezo-electric gauges cast into both ends and in the middle. Another zo-electric gauge, in form somewhat like a sparking-plug, was constructed perate under fluid pressure, and this gauge was screwed into the body he helmet-cylinder in order to measure the oil-pressure under the main ton.

Before proceeding to actual driving-tests, some tests were carried out he impact-testing machine with a short concrete specimen and a 200-lb. mmer. Amongst these tests was one, intended to serve as a guide to the eral behaviour of the helmet as a machine, which culminated with an lurance test of one thousand consecutive blows delivered from a height 3 feet. This test indicated that the general mechanical behaviour of helmet was satisfactory. Leakage of oil, which was of a medium ricating grade having a Redwood viscosity of 940 seconds at 21° C., was ht and could be completely overcome by fitting a hydraulic packing-g. There was no rebound of the hammer, and the steady working nperature of the helmet was well within practical limits.

For the practical pile-driving tests a piling frame with a 500-lb. drop-mmer was used. The ratio $\frac{\text{weight of hammer}}{\text{weight of 1 foot of pile}}$ was approximately 30, ich is the minimum value that should be used.[1]

Records were made of the stresses in the model pile at its head, middle d foot, and of the oil-pressure in the helmet, for several heights of mmer-drop and at a number of stages in the driving. Some set-records

[1] "Notes and Practical Suggestions on Pile-Driving." Journal Inst. C.E., vol. 2 35–36), p. 587. (April 1936.)

were taken, and a few comparative tests were carried out with the helı
replaced by felt packings of different thicknesses.

The first stress–time record was taken at the fourteenth blow, the
having been properly started, and this record, together with observati
of set, indicated easy conditions of driving. It was consequently deci
to drive the pile a little farther before taking a definite set of stress-recor
This was done, and at the forty-fourth blow a series of records
commenced.

TABLE I.

Blow No.	Packing.	Height of drop: inches.	Set: inch.	Maximum str lb. per square i
44	Helmet	24	0·66	1,296
48	,,	36	0·77	1,716
54	Eight ¼-inch felts	24	0·60	2,268
57	,, ,,	36	0·87	3,437

Details of this series of set- and stress-records are given in Table
It will be seen that the maximum stresses induced with a packing
eight ¼-inch felts are in this instance considerably greater than those w
the hydraulic helmet, although there is little difference in the recorded s
with both types of packing. In all cases where felt packing was used
comparative tests it was placed directly on the top of the pile withou
helmet of any kind.

In the earlier tests in the impact-machine it was found that the stre
time curve for the head of the specimen and the corresponding oil-pressu
time curve for the helmet were almost identical in form, the chief differe
being the presence in the oil-pressure record of high-frequency vibratio
These vibrations are, however, diminished by the mass of the helmet a
so do not appear on the stress-records.

During driving-tests oil-pressure records were also taken, and, as
correspondence with the head-stress record was found still to hold go
no further mention need be made of these records.

TABLE II.

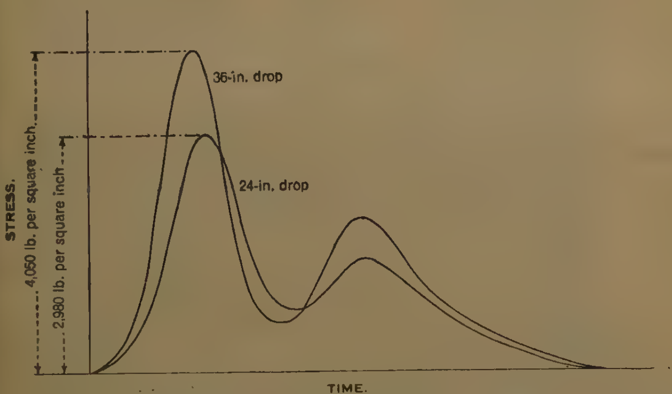
Blow No.	Packing.	Height of drop: inches.	Set: inch.	Maximum str lb. per square i
158	Sixteen ¼-inch felts	24	0·125	2,980
165	,, ,,	36	0·25	4,050
172	Twenty-four ¼-inch felts	24	0·125	2,750
	,, ,,	36	0·275	3,440
185	Helmet	24	0·125	2,915
186	,,	36	0·28	3,630

Table II gives details of a further series of records in which the hydra
helmet has been compared with two felt packings, consisting of sixt
and twenty-four pieces of ¼-inch felt respectively.

For the 24-inch drop the sets with all three packings are identical, the imum stress being greatest with sixteen felts and least with twenty- felts; the stress with the helmet is intermediate in value. These arks apply also to the 36-inch drop, except that the set with sixteen is slightly less than that with either twenty-four felts or with the het. It follows that the hydraulic helmet is roughly equivalent to a aber of felts of the above type, this number being less than twenty- and greater than sixteen.

The felts used in these tests were ¼ inch thick when new and had been tly consolidated, and from the results of previous tests it appeared that stiffness-factor was approximately 15,000 lb. per square inch per inch sixteen felts and 10,000 lb. per square inch per inch for twenty-four s, at a stress of 3,000 lb. per square inch. In practice the stiffness-

Fig. 2.



Head-Stress with Sixteen ¼-inch Felts.

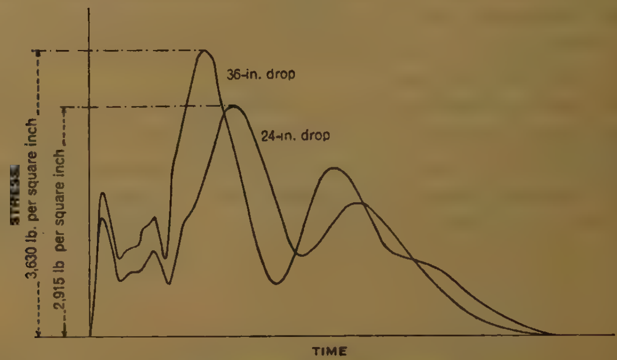
tor of packings may vary between 10,000 and 40,000 lb. per square inch inch at the above stress, and a value of 20,000 lb. per square inch per h represents a packing of medium stiffness. Therefore it can be umed that the hydraulic helmet gives a performance superior to average t packing.

Figs. 2 and *3* (p. 336) show the stress–time curves for the head of the e under the conditions given in Table II, for sixteen felts and for the draulic helmet respectively.

At the two-hundred-and-fifteenth blow the model pile had penetrated out 9 feet 6 inches, and the test was completed with three blows, at feet, 2 feet, and 1 foot drops, respectively. The final sets under these ows, and using the hydraulic helmet, were 0·18, 0·125, and 0·02 inch pectively. A final stress-record showing head- and foot-stresses at the t 36-inch blow is given in *Fig. 4* (p. 336).

Except for the few blows given when using felt packing for co-
parative purposes the pile was driven throughout with the hydrau
helmet.

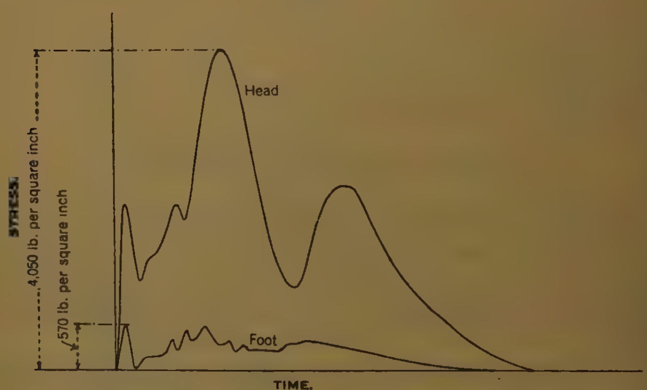
Fig. 3.



HEAD-STRESS WITH HELMET.

It was noticed in preliminary tests in the impact-machine that, w
the helmet, a high initial peak-stress was induced, but it has been sho
that in driving a pile with a hammer of the correct weight this initial pe

Fig. 4.

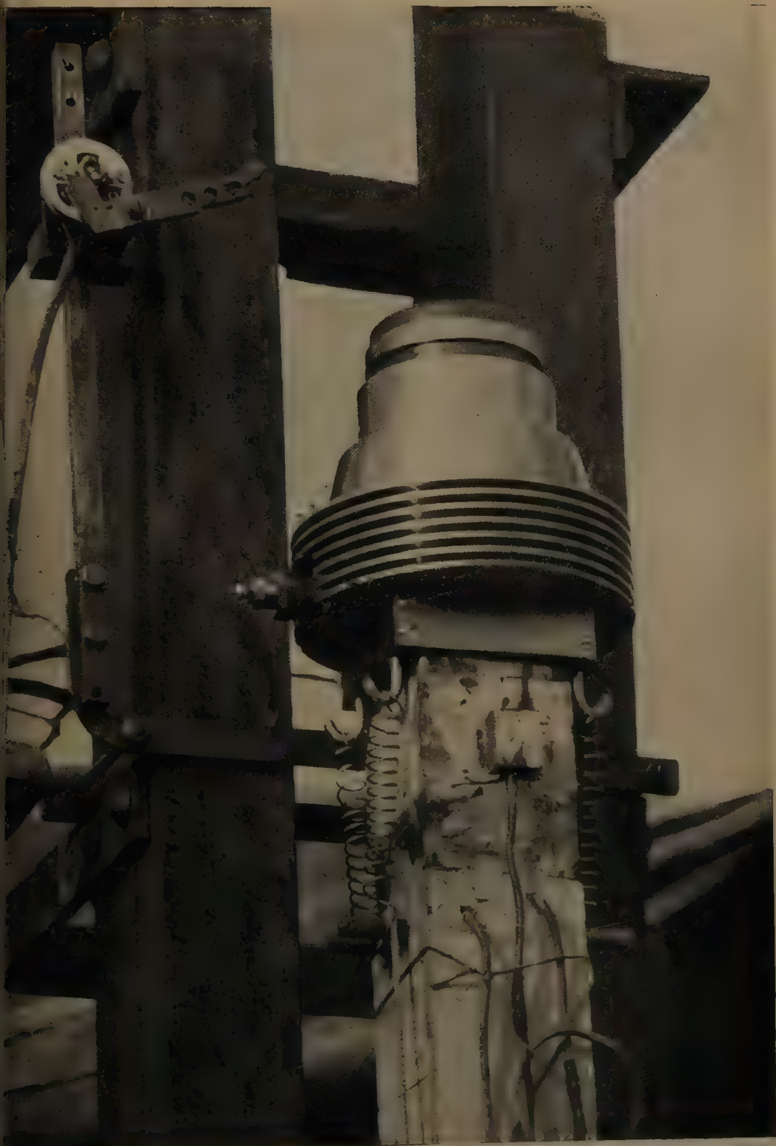


FINAL PILE-STRESSES WITH HELMET.

is of no importance. It still persists, as shown by *Figs. 3* and *4*, but i
of relatively reduced magnitude and is not the maximum stress in the p

The ideal constant-pressure curve, aimed at in the design-theory, l
not yet been realized. This is due mainly to two reasons: one is t
presence of peaks in the pressure-curve, due probably to inertia of t
working fluid and reflected stress-wave; the other is lack of informati

Fig. 5.



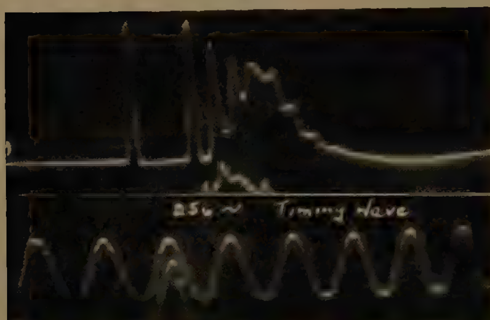
HELMET MOUNTED ON MODEL PILE.

Figs. 6.

(*a*)

2½-ton hammer with 5-cwt. helmet.

(*b*)



200-lb. hammer with 20-lb. helmet.

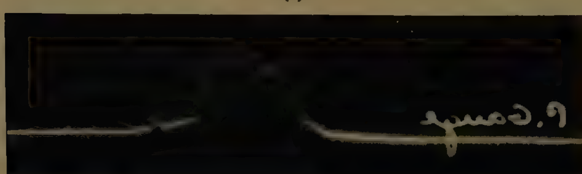
RECORDS OF DECELERATION OF PILE-DRIVING HAMMERS.

Figs. 7.

(*a*)

Deceleration of hammer recorded by piezo-electric deceleration-recorder.

(*b*)



Stress in specimen, for similar conditions.

DECELERATION OF HAMMER AND STRESS IN SPECIMEN (DURATION OF BLOW = 0·01 SECOND).

garding coefficients of contraction and velocity for the discharge-orifice. me efforts have been made to calculate approximately the coefficient of charge for the orifice as constructed, and it appears that for this particular type the factor varies between 0·4 and 0·9 during the stroke of the ston. It depends on oil-pressures, velocity and form of orifice, all of hich vary during the blow, and it is consequently impossible to give finite values without further research.

A photographic view of the hydraulic helmet in position on the model e is given in *Fig. 5* (facing p. 336).

nclusions.

The results of the tests described above, and of a number of others the impact machine, have shown the possibility of constructing a actical hydraulic-buffer packing and helmet combined, which will tisfy the requirements of a good packing. Constant stress in the model e during the period of the blow was not obtained in these tests.

The problem of pre-determining the shape of the stress–time curve is osely linked with that of determining coefficients of contraction and locity for the drowned orifice used in the helmet. Provided that this tter problem were solved, then by selecting the time of the blow such that reflected stresses could reach the head during this period, pre-determination might be possible.

In pile-driving the hydraulic helmet compares favourably with a packing felt, with the additional advantage of non-consolidation.

The Peak-Stress Indicator.

Simple Instrument for Measuring the Maximum Impact-Stress at the Head of a Driven Pile.

Research on the driving of reinforced-concrete piles, carried out at e Building Research Station, has shown that the stresses most important producing driving failures are the maximum compressive stresses at e head and foot, and in earlier accounts, describing the research,[1] ethods for the estimation of these stresses were presented, including a ries of charts for use in detecting dangerous conditions at the head and ot. The main difficulty in applying the charts is that it is usually possible form only a very rough estimate of the stiffness of the head-cushion, hich largely determines the stresses. Attention has therefore been rected towards the development of a simple instrument, the "peak-tress indicator," for the direct measurement of the maximum compressive ress at the head. The use of the instrument not only introduces certainty to the examination of one danger-point—the head—but also allows the

[1] Footnotes 1 and 2, p. 331.

conditions at the foot to be assessed with greater accuracy than is possib from the charts alone. This and other uses of the peak-stress indicat are discussed later.

The original design for the indicator, which is screwed to the upp surface of the hammer and measures its maximum deceleration, w described in the above-mentioned accounts, but this form was subs quently found to be subject to errors when used under practical condition A satisfactory instrument, simple in construction, has now been evolvec the modifications, which have been introduced to eliminate the errors, a now described.

Factors Affecting the Design of the Peak-Stress Indicator.

An approximate mathematical analysis of the deceleration of th hammer during impact resulted in an equation of the following form :—

$$\text{Decleration} = A \sin mt + B \sin m't \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

The expression for the force on the pile-head has a similar form,

$$\text{Force on pile-head} = C \sin mt + D \sin m't \quad . \quad . \quad . \quad . \quad (2)$$

The deceleration of the hammer is made up of two periodic terms, th first of frequency $\frac{m}{2\pi}$ and the second of frequency $\frac{m'}{2\pi}$, and in designing th original form of the indicator it was assumed that the second term, whic has a high frequency compared with the first, might be neglected. If th assumption is correct, then the force on the pile-head at any moment equal to the product of the mass and the deceleration of the hammer, ar measurement of the maximum deceleration of the hammer immediatel provides a measure of the maximum stress in the pile-head. The origin indicator consisted of a small weight, forced upwards against an insulate stud by a spring, whose compression was adjusted by a calibrated screw head; an electric circuit signalled the breaking of contact. On impac the small weight, which underwent the same deceleration as the hamme exerted a downward force on the spring tending to open the contact which, however, remained closed unless the product of the mass of th weight and its maximum deceleration exceeded the spring force. B adjusting the calibrated screw until the contact just opened, the maximu deceleration of the hammer could be measured. The arrangement of th indicator has already been shown on p. 158 of the first account of th work,[1] but the indicating circuit has been slightly modified. In practi it was found that, although the device was satisfactory where no helm or only a very light helmet was used, for normal conditions it might inaccurate, due to the second periodic term in the expression for t

[1] Footnote (1), p. 331.

celeration. Calculations showed that the frequencies $\frac{m}{2\pi}$ and $\frac{m'}{2\pi}$ would,
practice, be of the order of 50 and 500 cycles per second respectively,
d that the deceleration of the hammer due to the second term might be
5 times that due to the first. The effect of the helmet, which is respon-
ble for the high-frequency term, must therefore be taken into account.
xperimental measurements, obtained by piezo-electric methods,[1] con-
med this conclusion, as may be seen from *Figs. 6* (facing p. 337), giving
cords from tests on model and full-scale piles. It can also be shown,
owever, that, although the second term is of considerable importance in
e expression for the deceleration, it has only a minor effect on the stress
the head of the pile ; a reasonably accurate measure of the head-stress is
ven, therefore, by the maximum value of the first term only. *Figs. 7*
acing p. 337) illustrate this on the model scale. The modifications of
e instrument have been designed to reduce, as far as possible, the
alue of the deceleration due to the second term in equation (1).

ethods of Eliminating the Error due to the Helmet.

Two methods of reducing the effect of the second term have been
evised :—

(*a*) *The Damped-Spring Mount.*—The ratio of approximately 10
etween the low- and high-frequency components of the decleration sug-
ested that if the simple indicator were mounted on a spring, critically
amped by an oil dash-pot and possessing a natural frequency having a
uitable value intermediate between those of the two components, the
ffect of the higher frequency would be reduced, without appreciably
ffecting the contribution of the lower frequency. Calculations showed
hat by choosing a frequency of 150 cycles per second for the spring the
rrangement would have the desired effect, provided that the high and low
requencies differed sufficiently in numerical value and that the magnitude
f the high-frequency term was not excessive.

Both model and full-scale practical tests were carried out. A model
elmet and dolly were constructed, their dimensions and physical constants
eing suitably adjusted to reproduce typical practical conditions, as
evealed by previous pile-driving research. The model-tests were con-
ucted with the impact-machine and the 200-lb. hammer used in the pile-
riving investigation. Full-scale tests were carried out with hammers
eighing $1\frac{1}{2}$, $2\frac{1}{2}$, and 4 tons, under normal practical conditions.

As a result of the tests it was concluded that, with the modified in-
trument, head-stresses can be measured with a possible error of about
10 per cent., provided that the working conditions are such that the fre-
uency of the oscillations due to the helmet is kept high (over 500 per
econd). Two main factors control this frequency ; namely, the weight

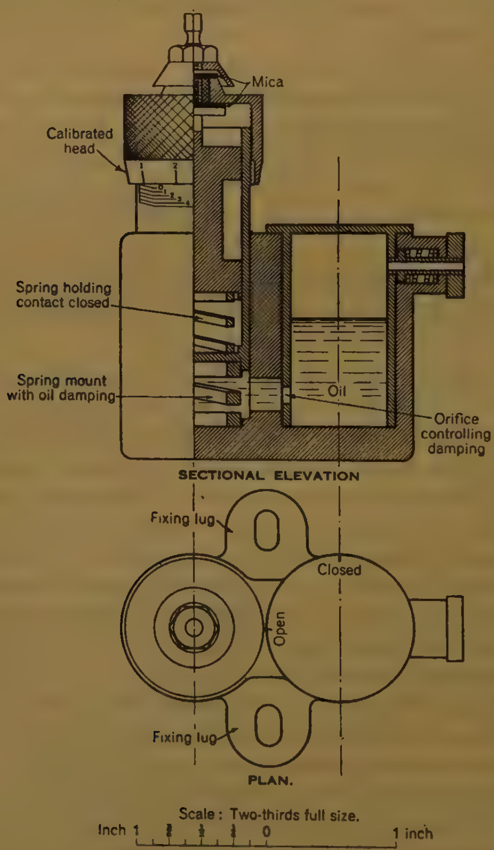
[1] Footnote (1), p. 331.

of the helmet and the stiffness of the dolly. For accurate results the ra

$$\frac{\text{weight of helmet in lb.}}{\text{cross-sectional area of dolly in square inches}}$$

should not exceed 3, and the dolly should be of hardwood, in good co dition, and not more than 15 inches long.

Figs. 8.



PEAK-STRESS INDICATOR.

Figs. 8 show a peak-stress indicator for practical use, incorporatin the modifications discussed above. The instrument is small and ligh and is attached to the upper surface of the hammer by two screws. twin flexible lead with spring terminals (not shown) connects the indicat to a box housing a neon lamp and batteries.

(*b*) *The Delayed-Break Method.*—A simpler method of modifying th

original peak-stress indicator, to render it insensitive to the second term in the expression for the deceleration, is also being developed. This has the advantage of requiring no oil-damping, but it has not yet been subjected to practical tests.

The principle of the modification may be understood by considering two sinusoidal oscillations of frequency n_1 and n_2. For a given acceleration it is easily shown that if y_1 and y_2 denote the corresponding displacements, then

$$\frac{y_1}{y_2} = \left(\frac{n_2}{n_1}\right)^2.$$

It has already been stated that in a typical case the ratio of the high frequency to that of the low, in the expression for the deceleration, is about 10. The displacement of the peak-stress indicator due to a given acceleration is therefore 100 times as great for the low-frequency term as for the high-frequency term. If, then, the contacts are arranged so that a small movement of the weight is allowed without breaking the electric circuit, it should be possible to eliminate the effect of the high-frequency deceleration without any serious inaccuracy in the measurement of the low-frequency component.

It is proposed to provide this delayed break by inserting a small cantilever spring between the contacts, arranged so that when the contacts tend to open, due to the deceleration of the weight, the spring relaxes and maintains contact over the required distance.

The Electric Circuit for Signalling the Breaking of Contact.

The electric circuit for indicating the breaking of contact is arranged so that any interruption of the circuit causes a small neon indicator-lamp to glow; the lamp remains alight until the circuit is reset by operating a switch. The circuit requires a 100-volt dry battery and a 2-volt accumulator.

The box containing the batteries and neon lamp may be placed at any reasonable distance from the indicator. There is nothing fragile in the apparatus and it requires no attention other than battery-maintenance.

Calibration.

The instrument is calibrated statically in terms of deceleration. It is only necessary to determine the mass of the weight and top spring, the stiffness of the spring, and to calibrate the thread of the adjusting screw controlling the compression of the spring in terms of movement per scale-division. It is then a simple matter to draw a graph relating the divisions of the screw-head to deceleration, which is given in units of g, the acceleration due to gravity. The calibration is linear and in the experimental models has been found to change little with time. A slight drift of the

zero position may occur, but this can be allowed for by addition or su traction as the case may be.

The Use of the Peak-Stress Indicator.

The procedure for measuring the maximum compressive stress at t head of a pile for a specified height of fall of the hammer requires t delivery of about half-a-dozen blows, and is as follows :—

The indicator is screwed to the upper surface of the hammer, the lea are connected, and the box containing the indicating lamp is placed in convenient position. The adjusting screw is set to a high decelerati and the circuit is switched on. A blow is delivered with a specified heig of fall. If the lamp does not light, the deceleration to which the indica is set is too high and must be reduced for the next blow. If the lam now lights, the correct deceleration lies between the first and second settin and, for the next blow, the setting of the screw should be half-way betwe these settings. This procedure is continued for several blows, alwa setting the indicator for the next blow half-way between the high setting at which the lamp has come on and the lowest setting at which has remained dark. With this method half-a-dozen blows are suffici to establish the correct deceleration within 2 or 3 per cent. To dedu the pile-head stress in lb. per square inch the deceleration in units o has to be multiplied by the combined mass of the hammer and helmet lb., divided by the area of the pile-head in square inches.

A valuable use of the indicator is in the examination of the causes head-failure. In the absence of any knowledge of the head-stress it generally difficult, if not impossible, to decide whether failures are to ascribed to the driving conditions or to the methods used in the manu facture of the pile. A knowledge of the maximum compressive stress the head and of the constitution of the concrete will immediately ena a decision to be made. It is suggested that the examination should made in the following way :—

At the first sign of failure the indicator should be attached to t hammer, and a reading of the maximum stress obtained as described abo The measured stresses should not exceed 50 per cent. of the cube compr sive strength of the concrete. With careful control in manufacture $1 : 1\frac{1}{2} : 3$ mix will withstand an impact stress of 3,000 lb. per square inc and a $1 : 2 : 4$ mix a stress of 2,000 lb. per square inch, but these valu of the stress should not be exceeded if head-failure is to be avoide Failing-stresses much lower than these values are an indication that t concrete is not developing its full impact-strength, and that greater ca in manufacture is required. Isolated cases of low stress may, howev be due to uneven stress-distribution caused by badly-placed packing, b such cases are easily recognized. Nevertheless, conclusions should based upon the examination of several piles.

The instrument can also be used for examining the stresses at the foot of the pile, but the necessity for this does not arise so frequently as the question of head-conditions. The foot-stresses are dependent on the set and the ground-conditions as well as on the head-conditions, and in general cannot be determined from the head-stress and the set alone. The foot-stresses can be determined from these factors alone only when it is known that the foot is penetrating a dense stratum, in which case driving resistance is concentrated at the foot, and skin friction may be neglected. The method of procedure is as follows :—

Suppose it is required to determine whether the maximum compressive stress at the foot exceeds 3,000 lb. per square inch, this value being the highest permissible stress in the pile. First, with the indicator on the hammer, the maximum head-stress is adjusted to 3,000 lb. per square inch by variation of the height of fall of the hammer. With this head-stress the elastic and plastic sets are then recorded with the set-recorder described and illustrated previously * and from the record the equivalent elastic set is determined. This is given by the expression :—

Equivalent elastic set = twice plastic set (or permanent set as ordinarily measured) + elastic set (or earth-movement).

The charts shown in *Figs. 2*, *3*, and *4*, facing p. 592 of the second account of the work,* are now used. First, from the usual allowances for friction and other losses, the height of free fall is determined, and then, from *Fig. 4* of that account * the effective height of fall is obtained. From the curves for the maximum effective height of fall (*Figs. 3* *) the approximate condition of the packing (hard, medium or soft) is determined. (To do this it is necessary to employ *Fig. 2* * to find the ratio

$$\left(\frac{\text{weight of hammer and helmet}}{\text{weight of 1 foot of pile}}\right).$$

Finally, the measured equivalent elastic set is compared with that obtained from the appropriate curve in *Figs. 3* *. Sets greater than, and falling above, those given by the curve are accompanied by stresses lower than 3,000 lb. per square inch. Sets smaller than those given by the curve denote higher stresses, and consequently indicate dangerous conditions at the foot.

A New Method of Determining the Stiffness-Factor, k/A, for Ordinary Packing Materials.

In the earlier † work on packing materials the stiffness-factor for the material was derived from stress–strain curves which had been obtained by plotting maximum stress against maximum strain for selected heights of drop. The stress was recorded by a piezo-electric gauge mounted on a

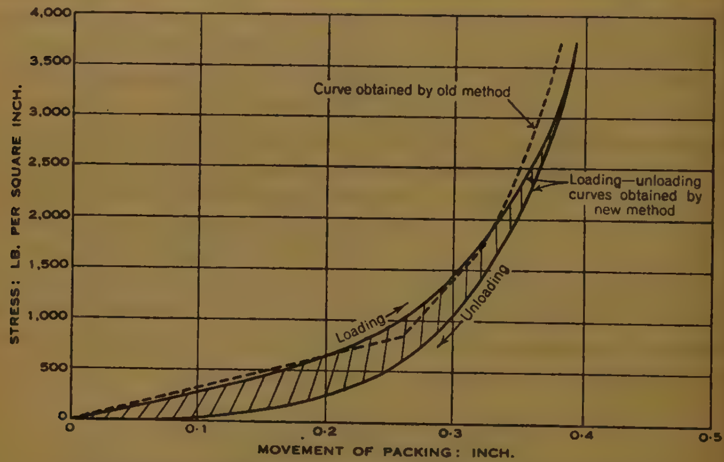
* Footnote (2), p. 331.
† Footnote (1), p. 331.

special anvil, and the strain by the trace of a stylus fixed to the hamm and recording on metallic paper mounted rigidly in a suitable frame.

A new method of finding the value of k/A has been developed, by mea of which the stiffness-factor may be obtained for any stress up to t maximum value recorded on a single stress–time curve. The method briefly as follows :—

A stress–time curve, for the given packing material, is recorded in t usual manner using the special anvil. The weight of the moving part the anvil is small compared with that of the hammer, and consequent by a simple adaption of the stress-scale, the record may be regarded as retardation–time curve for the hammer and moving part of the anv combined.

Fig. 9.



Stress–Displacement Curves fot Twenty $\frac{1}{4}$-inch Felts.

Double integration of the curve, with correct selection of the base for the integral curves, gives a displacement–time curve for the packing under test.

Combining this latter curve with the stress–time curve, a stress– displacement curve for the packing material, under dynamic loading, is obtained. The stiffness-factor is then obtained from the relation

$$k/A = \frac{P^2}{2(\text{Area under stress–displacement curve})}$$

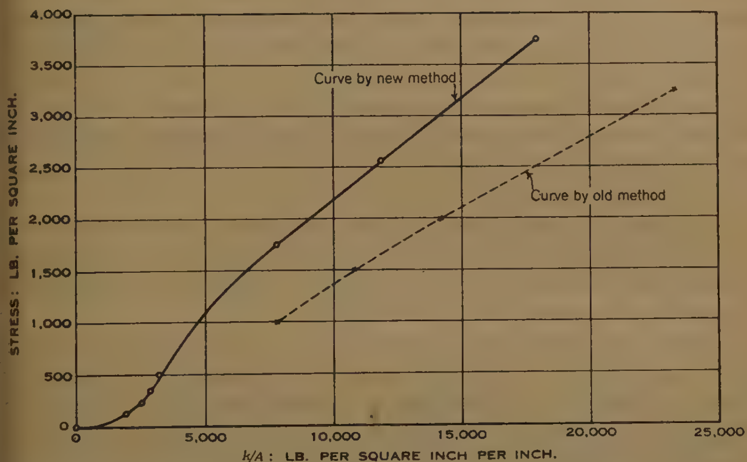
where P denotes the stress.

As an illustration of the method, the stiffness-factor has been determined for a packing of twenty $\frac{1}{4}$-inch felts, making use of the stress-record obtained during previous tests.

The stress–displacement curve derived from the stress-records is shown in *Fig. 9*, together with the corresponding curve obtained by the old

method. It will be seen that the new method gives results which agree fairly well with those previously derived. In addition the new method gives the dynamic-unloading curve. The shaded area between the loading and unloading curves represents the energy lost in the packing, which is information not previously obtainable.

Fig. 10.



VARIATION OF k/A WITH STRESS FOR TWENTY $\frac{1}{4}$-INCH FELTS AFTER 2,004 BLOWS.

The stress–stiffness curve is given in *Fig. 10* and it is noteworthy that the values of k/A obtained by the present method are much lower, for corresponding stresses, than those previously obtained. This fact is due to the manner in which the original stress–displacement curve (*Fig. 9*) was smoothed into an ideal curve, giving lower values to the area under this curve.

REPORT OF THE BUILDING RESEARCH BOARD FOR THE YEAR 1937.*

Particular attention is drawn to the present position of research on soil mechanics. Assessing the work done on this subject in different countries according to the number of research workers engaged, data compiled for the First International Conference on Soil Mechanics and Foundation Engineering indicated that Great Britain lagged behind in 1936 with two only, compared with at least seventy-six in America, at least sixteen in Japan, at least fifteen in Germany, six in Holland, and five in Austria. There were, however, signs of an increased consciousness

* Published by H.M. Stationery Office, price 3*s*. 6*d*.

of its value in Great Britain, and the staff at the Building Research Stat devoted to this subject has been strengthened and a section establish at the Road Research Laboratory for investigation on the aspect of subject of specific application to roads. Further development of t work is urgently needed, and it is hoped that support may be forthcomi from outside bodies which will enable the work to be expanded.

Soil mechanics is one of the researches at the Station which is bei assisted by this Institution. Other such researches mentioned in t report are pile-driving, vibrated concrete and special cements for la dams.

Among new investigations proposed or put in hand during the ye mention is made of researches on the strength, stability, and weath resistance of brick masonry, on heat-transmission through roofs, and plain clay tiles for roofing.

Preparation is being made for the publication of the results of t recently concluded research on reinforced concrete carried out in e tension of the earlier work on creep, cracking, bond and strength reinforced-concrete structural members.

A Paper † published during the year on the stability of foamed bla furnace slag marked the close of a successful effort to utilize the by-produ of another industry. Foamed slag has proved suitable as an aggrega for light-weight concrete. The value of air-cooled slag as a heavy concre aggregate is now being studied.

A "spray" method evolved at the Station of cleaning Portland an Bath stone, which does not involve hard scrubbing, has proved successf in practical tests by His Majesty's Office of Works. The study of the effe of the moisture relations of building stones on their durability and oth properties has been continued. Work has also been carried out on cl building materials, sand-lime bricks, and generally on the properties porous bodies. Asphalt and bitumens have been studied with particul reference to roofing and floor materials.

Research has been carried out on the constitution of cement, and 3 years' study of asbestos-cement roofing materials has been conclude Limes, plasters, and external rendered finishes have been studied. I connexion with the last-mentioned, a survey of continental methods rendering has proved very instructive. A study has been made of th factors controlling the adhesion of oil paint to plasters.

Research on structures includes short-period tests to destruction o long reinforced-concrete columns, the relief of stress with time in pre tensioned reinforcement, surface-finishes of concrete, strength-tests f cement-mortar cubes compacted by vibration, strength of reinforced brick beams, and stability of a masonry wall.

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† T. W. Parker, "Foamed Blast-Furnace Slag." Iron and Steel Institute, Speci Report No. 19, 1937.

The investigation of the strength of existing road-bridges commenced in 1936 has continued. Following the study of the mechanism of failure of voussoir arches by Professor A. J. S. Pippard on behalf of the Station, the behaviour of this type of structure when built of normal materials is being studied. The work at the Fire Testing Station during the year is described. The shielding effect of a surrounding built-up area on the wind-pressure on a building is being investigated on a model scale in a large wind-tunnel at the National Physical Laboratory.

In connexion with the efficiency of buildings from the standpoint of the user, research on heat-transmission and measurement, ventilation, condensation and acoustics have continued.

In addition, a large number of special investigations have been carried out.

REPORT OF THE NATIONAL PHYSICAL LABORATORY FOR THE YEAR 1937.[1]

In the Report a review is given of the activities of the several departments during the year, but it is only possible to note here a few of the researches in progress.

In the Physics Department, the determination of thermal conductivity has continued. In connexion with refrigeration, evaporation of water from moist surfaces has been studied. X-ray diffraction methods have been applied to studies of the structure of electro-deposited chromium, fatigue-failure, the effect of cold work-hardening, etc. An investigation has been made of sound-transmission through partitions and floors.

In the Electricity Department, work has been done on standards of inductance and on the measurement of very high frequencies. The dielectric properties of synthetic resins have been investigated. In connexion with high-voltage research, the effect of impulse voltages on transmission-lines and equipment has been studied. In photometry the effect of the colour of a street-lighting system on the ease with which objects in the roadway can be detected and the problem of glare have been studied. In radio research the work in connexion with the propagation of radio waves and direction-finding has continued.

The Metrology Department has studied the effect of humidity on the refraction of air. The absolute determination of the acceleration due to gravity at Teddington has been completed.

In the Engineering Department the application of X-ray diffraction methods to the study of the fundamental aspects of the deformation and fracture of metals has proved successful in revealing important facts relating to the mechanism of failure of metals under stress. An investi-

[1] Published by H.M. Stationery Office, price 2*s*. 6*d*. net.

gation of materials for cast crankshafts and their behaviour under fatig conditions has been completed. Research is being initiated into corrosion of metal surfaces in contact and subject to vibration. A rep has been issued on the variation in wind-pressure over a wide front a result of experiments carried out at the River Severn bridge. A stu of the specific heat of gases by the explosion method has been conclud Among new investigations commenced may be mentioned the streng of welded constructions for pressure-vessels, a study of creep relaxation the flanges and bolts of pipe-flanges at high temperatures and pressur the effect of surface-finish on the fatigue-strength of steel strip, and t silencing of motor-cycles.

Further research on the production of pure iron is reported by t Metallurgy Department. Studies of alloys of nickel and chromium a ternary alloys of iron, nickel and chromium have been completed, and wo has also been done on alloys of iron and manganese. The study of terna alloys and more complex systems has been extended by the use of X-r methods. An investigation of the properties of aluminium and magnesiu has progressed. A study of the creep-properties of metals for use at hi temperatures has been concluded. Work has also been done on int crystalline cracking.

In connexion with Aerodynamics, research has been carried out on t stability and control of the low-wing monoplane. A study of boundar layer flow and the breakdown of laminar into turbulent flow has be continued. Full-scale research on airscrews and work on flutter an buffeting have been carried out during the year.

In the William Froude Laboratory researches on the resistance, propu sion and pitching of ships in rough water and on the effect of blade are position and immersion of screw propellers have been continued. Ca culations have been made of the wave-resistance of 3-dimensional form An investigation has been started on the effect of the shape of the bow the resistance of a ship. Another research concerns the effect of modera helm angles on the propulsive efficiency of single- and twin-screw vesse

REPORT OF THE WATER POLLUTION RESEARCH BOAR FOR THE YEAR ENDING 30 JUNE, 1937.*

Attention is drawn to the passing of the Public Health (Drainage Trade Premises) Act, 1937, which comes into operation on the 1st July, 193 This follows recommendations made by the Joint Advisory Committ on River Pollution to the effect that local Sanitary Authorities should under a general obligation to receive and dispose of the industrial effluen of their districts, and that traders should have a correlative right to di charge such effluents into the public sewers. After considering th

* Published by H.M. Stationery Office, price 9*d*.

sition with regard to river pollution which has developed in consequence the passing and operation of the Land Drainage Act, 1930, the Joint dvisory Committee have recently recommended[1] that immediate nsideration should be given to the question of the formation of river uthorities, in whom should be centralized the functions relating to prevention of pollution, land-drainage, fisheries, abstraction of water, and, suitable cases, navigation. Mention is made in the Report of the rmation early in the year under review of a central Water Advisory ommittee as recommended in the report of the Joint Committee on ater Resources and Supplies.[2] Particular reference is made to the rvey of the river Tees and the investigations of the estuary of the river ersey. The chemical, biological, and hydrographical survey of the rmer has been completed with the issue of a report dealing with the on-tidal reaches of the river.[3] The investigation of the river Mersey egun in 1933 with the object of determining the effect of the discharge f crude sewage on the amount and hardness of the deposit in the estuary as been completed, and a final Report has now been published.[4]

In the report of the Director of Water Pollution Research attention is rawn to the study of the effects of various conditions, including temperaure, on the efficiency of the process of softening water by means of baseexchange zeolites. Following the discovery that a satisfactory baseexchange material can be prepared from Fuller's earth, experiments have een carried out with other British clays, but none has proved equally uccessful. Recent work on the base-exchange and acid-exchange roperties of synthetic resins has shown that the values of the resins vary ot only with composition but with the detailed conditions of preparation.

An investigation carried out to determine the action of water on lead ervice-pipes has shown average concentrations of lead in solution ranging rom 0·1 to as much as 0·5 part per million.

Good progress has been made with methods of treatment of the polluting aste waters from dairies and creameries, and experimental work has been ontinued in two directions—the activated-sludge process and the use of wo percolating filters in series.[5] Further research has been carried out nto the biochemical changes which occur in the activated-sludge process f treatment of sewage. In this connexion the effect of the addition of ewage and proteins on the coagulation of suspensions of fine particles y electrolytes has been studied.

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[1] Fourth Report. H.M. Stationery Office, 1937.

[2] Report for Session 1935–36. H.M. Stationery Office, 1936.

[3] "Survey of the River Tees; Part III, The Non-Tidal Reaches—Chemical and iological." Water Pollution Research Technical Paper No. 6. H.M. Stationery ffice, 1936.

[4] A notice of this Report appears on p. 350, *post*.

[5] A. Parker, "The Treatment and Disposal of Trade Waste Waters." Trans. nst. Chem. E., vol. 16 (1938). *Also abridged report in* Journal Inst. C.E., vol. 8 1937–38), p. 285. (March, 1938.)

EFFECT OF DISCHARGE OF CRUDE SEWAGE INTO TH ESTUARY OF THE RIVER MERSEY ON THE AMOUNT A HARDNESS OF THE DEPOSIT IN THE ESTUARY.

Water Pollution Research Technical Paper No. 7*, issued by Department of Scientific and Industrial Research, gives a report on above investigation which has been in progress since 1933. As a resul the inquiry it is found that the crude-sewage discharge into the estu of the river Mersey has no appreciable effect on the amount of hardnes the deposits in the estuary.

ENGINEERING RESEARCH IN THE ROYAL NAVAL COLLEGE, GREENWICH. MAY, 1938.

Although a number of the subjects investigated experimentally a analytically in the Engineering Laboratory in the Department of Appl Mechanics under the direction of Professor B. P. Haigh, M.B.E., D.S are of specialized Naval interest, other subjects of more general inter are mentioned in the following notes.

Welding Research.

Earlier investigations carried out in the Laboratory were direc towards the development of optimum designs for right-angled and obli joints between rolled sections and composite sections in general use shipbuilding and in structural engineering, and to the comparison of su welded joints with standard riveted constructions. This work has b extended in different directions, and notably to the development optimum designs for oblique branch connexions and anchored bends high-pressure pipe-lines. Throughout these investigations, the use resin has been developed for revealing the distribution of strain in structures, and this method appears to be effective in revealing the grad spreading of plastic strain under increasing load or pressure.

Fatigue of Metals.

Fatigue cracking in welded and in riveted joints is being investigat in a large Haigh fatigue-testing machine that works with a range of lo of 6 tons and at a frequency of over 4 million cycles per working day 24 hours. A smaller machine of the same type is being used in connexi with other researches, on the fatigue strength of wire ropes with differe forms of end fastening, and on the fatigue of lead and different lead allo as used in pipes and in electric cable sheathings. It was in this same fatig

* Published by H.M. Stationery Office, price 30*s*.

achine that corrosion-fatigue was first investigated in 1916, the special ngers of conjoint chemical and mechanical action being then revealed in nnexion with vibration of steel and other metals immersed in sea water particular. Lead is remarkable in respect that fatigue is delayed when e surface of the specimen is moistened with water during the test, or hen the specimen is totally immersed in water, or even in acids that celerated chemical attack. A Haigh-Robertson bending-fatigue machine being used in researches on the corrosion-fatigue resistance of different pes of cold-drawn rustless steel. In this machine, the long thin test-ece in the form of a rod or wire is flexed by an axial load and is rotated a very high speed, imposing as many as 14 million cycles or more per y. The same machine, modified in certain details, is used also in testing pper and cadmium-copper trolley wires of large sections, either round or figure-8 profile.

lastic Yield and Cracking.

Plastic yield in mild steel is being investigated by extending to tensile sts precautions comparable with those more generally observed in fatigue sting. The test-pieces are formed with enlarged ends and generous ansition curves to eliminate the local concentrations of stress that are nerally disregarded in tensile testing, and are loaded through knife lges arranged to ensure truly axial loading without bending stresses. is found that the limit of elastic proportionality can be raised, in many rmalized or "as received" samples, to a value approaching or even ceeding the ultimate tensile strength of the mild steel. The high value this initial yield point ("higher yield point") appears to explain many nomalies that have been observed in practical experience. The lower ield point that is observed immediately plastic yield has commenced is eing investigated in a variety of mild steels suitable for different applica-ions, and is considered to afford a serviceable and exceedingly reliable asis for structural design. Cracking in ductile metals is being investi-ated, not only in relation to fatigue but also under complex stresses pproximating to "triple-tensile". Novel forms of notched test-piece, dmitting of precise calculation, are employed in cracking tests; and ther novel forms are employed for producing "triple-tensile" stress esulting in brittle fracture with little or no plastic deformation even in uctile metals. Thermal contraction is being investigated in particular s a cause of triple-tensile stress resulting in brittle fracture.

ther Researches.

Light alloys suitable for use in engine pistons are being tested in ifferent ways, including fatigue, and an engine is being arranged for vestigating torsional vibration, particularly in cam-shafts affected by he action of tappets and springs. The collapse of pipes under external

pressure is being investigated analytically and experimentally w particular reference to the effect of slight deviations from truly circu profile. A novel form of wind-tunnel, specially designed to give a strea of uniform pressure and speed through the working chamber, is bei employed in conjunction with an original design of weighing balance in variety of problems arising in practice. Lubrication and viscosity a also being investigated analytically and experimentally.

The researches indicated are being carried out by students workin in association with Professor B. P. Haigh, Asst. Professor F. W. Thorn Mr. T. S. Robertson, and Mr. C. H. Helmer.

NOTES ON RESEARCH PUBLICATIONS.

1. Engineering Construction.

) *Engineering Physics.*

(a) *Elasticity and other mechanical properties.*

eatment of stability problems by strain-energy methods, *Zeit. ang. Math.*, **18**, *57* (Eng. Abs. **1**, Con. *160*).

emarks on the more accurate calculation of the deflexion of beams and struts, *Phil. Mag.*, **25**, *678*.

ote on Galerkin's method for the treatment of problems concerning elastic bodies, *Phil. Mag.*, **25**, *628*.

pplications of the Galerkin method to the torsion and flexure of cylinders and prisms, *Phil. Mag.*, **25**, *634*.

exure with shear and associated torsion in prisms of uni-axial and asymmetric cross sections. *Phil. Trans. Roy. Soc. London, Series A*, **237**, *161*.

ough compressibilities of fourteen substances to 45,000 kg/cm^2, *Proc. American Academy of Arts and Sciences*, **72**, *207*.

eflexion phenomena in a fixed beam during impact, *J. Roy. Tech. College*, **4** (*2*), *292*.

he effect of pressure upon the elastic parameters of isotropic solids, according to Murnaghan's theory of finite strain, *Physics*, **9**, *279*.

atural and artificial rubber; the elasticity of long-chain molecules, *Nature*, **141**, *670* (Eng. Abs. **1**, Con. *161*).

ew knowledge on the fatigue effects under tensile-compressive stresses, *Rev. Technique Luxembourgeoise*, **29**, *294*.

(b) *Soil Mechanics.*

nproved method of soil study, *Eng. News-Record*, **120**, *515*.

raphical representation of the mechanical analyses of soils, *Proc. Am. Soc. Civ. Eng.*, **63**, *1861*.

xperimental studies on the deformation of sand masses due to vertical loads, *Bull. Earthquake Research Inst. Tokyo*, **14**, *553*.

etermination of elastic constants of soils by means of vibration methods: Part I Young's modulus, *Bull. Earthquake Research Inst. Tokyo*, **14**, *632*.

etermination of elastic constants of soils by means of vibration methods: Part II. Modulus of rigidity and Poisson's ratio, *Bull. Earthquake Research Inst. Tokyo*, **15**, *67*.

ecent advances in knowledge of the colloidal properties of clay suspensions and gels, *Am. Inst. Min. and Met. Engineers, Tech. Pub., No. 871, 1.*

The figure in heavy type is the number of the Volume; that in brackets the number f the Part; and that in italic type the number of the Page. In references o "Engineering Abstracts" the number of the Volume is given in heavy type, the ection is indicated by the abbreviation Con., Mech., Ship., or Min., and the number f the Abstract is printed in italic type. The scheme of tabulation is given in the anuary, 1938, Journal (pp. 475–477), to which reference should be made.

* When it is known that a reference will appear in an early issue of "Engineering bstracts" this fact is indicated by an asterisk.

(c) *Mechanics of fluids.*

Concerning the velocity- and temperature-distributions in plane and axially sy metrical jets, *Proc. Cambridge. Phil. Soc.*, **34,** *185.*

Some phenomena accompanying the flow of water through a horizontal orifice, *R Gén. Hydraulique*, **3,** *296* (Eng. Abs. **1,** Con. *208*).

New researches on flow through under-sluice gates, *Comptes Rendus*, **206,** *1166.* .

Scale-model study of various types of siphon spillways, *Ann. des Travaux Publics Belgique*, **39,** *9.*

Experiments on water-waves of translation in small channels, *Phil. Mag.*, **25,** *754.*

Experimental study of the transport of solids in a watercourse, *Rev. Univ. Min.* . *269* (Eng. Abs. **1,** Con. *199*).

Investigations of the transport of solids in the river Reno at Malalbergo, Italy, *A Lav. Pubb.*, **76,** *15* (Eng. Abs. **1,** Con. *198*).

(3) *Operations and methods.*

Quick setting of concrete : getting the fullest benefit from calcium chloride, *Concr* **46,** *7.*

(4) *Structures.*

(a) *Earthworks, foundations, etc.*

Equilibrium of a thin plate, symmetrically loaded, resting on an elastic foundation infinite depth, *Phil. Mag.*, **25,** *576* (Eng. Abs. **1,** Con. *120*).

Calculations for a beam of finite length on an elastic foundation, *Ann. Inst. Tech.* . *Bâtiment*, **3,** *16* (Eng. Abs. **1,** Con. *186*).

Design of pile foundations, *Proc. Am. Soc. Civ. Eng.*, **64,** *311.*

(b) *Dams, Retaining-Walls, etc.*

Punjab Irrigation Research Inst. Research Publications, **2.**

Graphical determination of exit gradient for some standard types of structures, *No.* .

Uplift pressures under a sloping floor, *No. 18.*

Relative efficiency of a vertical sheet-pile under a flush floor, *No. 19.*

Some notes on Khosla's principle of independent variables : Mutual interference equal piles at ends of a floor, *No. 20.*

Pressure-distribution under a floor having equal end piles and a varying intermedi pile, *No. 22.*

Graphical methods for the determination of pressure-distributions under some standa forms of irrigation works, *No. 21.*

*The propagation of setting-heat in large masses of concrete, *L'Elettrotecnica*, *178.*

Temperatures and stresses in mass concrete, *J. Am. Concr. Inst.*, **9** (Proceedin **34**), *497.*

The mechanics of fish in rivers (fish-passes, etc.) (continued), *Ann. des Travaux P de Belgique*, **39,** *131.*

Passive defence of large dams, *Mem. Soc. Ing. Civ. France*, **90,** *382.*

(c) *Capacity Structures.*

Wind-pressures upon an open tank, *J. Roy. Tech. College*, **4,** *318.*

(d) *Bridges, Arches, Roofs, Hangars, etc.*

The buckling of a beam by longitudinal forces, *Zeitschrift für angewandte Mathema und Mechanik*, **17,** *232.*

Influence of concentrated loads on position of neutral axis in beams, *Proc. Leeds Ph and Lit. Soc.* **3,** *Part VII, 421.*

The equation of the three moments of a continuous beam subjected to bending a axial stress with bending strength varying linearly along all its bays, *Atti della Rea Accademia Nazionale dei Lincei. Rendiconti, 1936*, (*6*) *24* ; (*9*) *273* ; (*10*) *354.*

rder on elastic bed, *Zeit. für angewandte Mathematik und Mechanik*, **17**, *224*.
oment equations. A method of analysis for continuous beams and rigid frames, *Univ. Washington Eng. Expt. Station Bull., No. 92*.
ethods of mechanical analysis of stress in rigid frames, *J. Roy. Tech. College*, **4**, *335*.
elative flexure factors for analysing continuous structures, *Proc. Am. Soc. Civ. Eng.*, **64**, *123*.
evelopments in the design of bridges, *Sci. et Ind.* (*Travaux*), **63**, *97* (Eng. Abs. **1**, Con. *173*).
he behaviour of welded and bolted beam column connections in static and fatigue bending, *Welding J.* (*New York*), **17**, (*3*), *Welding Res. Supp. 23*.
esearch work on wind-pressure in Belgium, *Engineering*, **145**, *498*.
he resistance of reinforced-concrete columns to eccentric loads, *J. Am. Concr. Inst.*, **9** (*Proceedings*, **34**) *401*.
ests on hinged joints in reinforced concrete, *Ann. Inst. Tech. du Bâtiment*, **3**, *35* (Eng. Abs. **1**, Con. *188*).
ffect of special anchorage on bond stress, *Concrete*, **46**, *12*.

(e) *Tunnels.*

new method of waterproofing subways and tunnels, *Concrete & Constr. Engg.*, **33**, *214* (Eng. Abs. **1**, Con. *163*).
oncrete lining for tube-railway tunnels, *Engineering*, **145**, *401* (Eng. Abs. **1**, Con. *191*).
he ventilation of long road tunnels, *Schweizerische Bauzeitung*, **111**, *225*.

(f) *Buildings.*

he prevention of vibration in buildings, *J. Chartered Surveyors' Inst.* (*Trans.*), **70**, *223*.
ome problems connected with porous building materials, *J. Soc. Chem. Ind.*, **57**, *195*.
ir raid protection of industrial buildings, *Soc. Ing. Civ. France Mem.*, **90**, *374*.
ir protection and building regulations, *Bauverwaltung*, **57**, *953*.
he protection of buildings from damage by lightning, *Power and Works Engineer*, **33**, *94*.

) *Railways, Roads* (*excluding rolling stock*).

rotection and passive defence of important railway sidings, *Mem. Soc. Ing. Civ. France*, **90**, *391*.
oil mechanics in road construction, *Inst. of Highway Engineers, Bull. No. 11, May 1938*.
Modern methods of study of soils for road foundations—liability to cracking of the soils through frost, *Bull. Technique de la Suisse Romande*, **64**, *85*.
hear strength of cohesive soils, *Bautech.* **15**, *400* ; *453*.
he economy of the marsh blasting process, *Forschungsgesellschaft für das Strassenwesen* ; *Forschungsarbeiten aus dem Strassenwesen*, **4**, *1937*.
he aggregate grading of bituminous roads, *Asphalt u. Teer*, **37**, *740*.
Report on the construction of thin bituminous surfacings, with particular reference to tar surfacings with bituminized filler, *Strasse u. Verkehr*, **23**, *392* ; *403*.
he use of coloured and decorative asphalt for roads and buildings, *J. Soc. Chem. Ind.*, **57**, *99*.

6) *Docks, Harbours, Canals* (*including the constructional aspect of Irrigation and Drainage*) *and Rivers, Coastal Works.*

Wave-pressure against guard blocks on a quay-wall, *Rev. Gén. Hydraulique*, **3**, *293* (Eng. Abs. **1**, Con. *194*).
Structural design of flexible-pipe culverts, *Public Roads*, **18**, *217* (Eng. Abs. **1**, Con. *202*).
Report for year ending April 1937 (printed by the Supt. Gov. Printing, Punjab), *Punjab Irrigation Research Inst.*

A new method of determining seepage from canals in areas of high water-table, *Punj Irrigation Research Inst. Res. Pub.*, **5**, *No. 7*.

(7) *Water Engineering.*

(a) *Supply.*

The Surface-Water Year-Book of Great Britain, 1935–36, prepared by Inland Wat. Survey Committee, *Ministry of Health and Scottish Office.*

The mechanical properties of lead water-pipes, *Engineering*, **145**, *285* (Eng. Abs. Con. *156*).

Experiments on pipe coatings, *Ind. & Eng. Chem.*, **30**, *294* (Eng. Abs. **1**, Con. *203*).

Iron and iron coagulants in the treatment of water, *J. New England. W. W. Assoc.* **51**, *437* (Eng. Abs. **1**, Con. *152*).

*Chemical methods of slime and algae control, *J. Am. Water. Assoc.*, **30**, *437*.

(b) *Power.*

Hydro-generated energy, *Proc. Am. Soc. Civ. Engineers*, **64**, *675*.

Estimation of the efficiencies of water-turbines from experiments on models, *Te Reports Tôhoku Imp. Univ.*, **12**, *475* (Eng. Abs. **1**, Con. *250*).

(8) *Sanitary Engineering.*

Estuary of the River Mersey—effect of discharge of crude sewage into the estuary the river Mersey on the amount and hardness of the deposit in the estuary, *Wa Pollution Res. Tech. Paper No. 7* (D.S.I.R.).

Research in sewage-chemistry, sewage-treatment, and stream-pollution, *Sewage Wor Journal*, **10**, *173*.

2. Mechanical Engineering.

(1) *Prime Movers.*

Materials for high-pressure, high-temperature steam service, *J. Am. Soc. Naval Engr* **50**, *52*.

Cost of energy-generation. Second symposium on power costs: Elements of co *Proc. Am. Soc. Civ. Eng.*, **64**, *638*.

(2) *Transmission and Conversion of Power.*

Highest frequency of torsional vibration, *The Engineer*, **165**, *542*.

The transmission of power by fluid couplings (Paper, Inst. of Mech. Engrs., April 2 1938), *Engineering*, **145**, *487*.

Deformations and fatigue of spiral springs of any form subjected to loads in an direction, *Science et Industrie* (*Mécanique*), **22**, *33* (Eng. Abs. **1**, Mech. *293*).

The action of belt drives at varying speeds, *Ricerche Ing.*, **6**, *1* (Eng. Abs. **1**, Mec *253*).

(3) *Applications of Power.*

Amenities of railway passenger travel (Paper, Inst. of Transport, April 11, 1938), *T Engineer*, **165**, *472*.

(4) *Measuring Instruments.*

The spectrographic analysis of certain materials to determine their conformity specifications, *J. Am. Soc. Naval Engrs.*, **50**, *39*.

Magnetic testing of materials, *Mitteilungen aus dem Kaiser-Wilhelm-Institut fü Eisenforschung*, **20**, *92*.

The Brinell hardness-testing method, *Instruments*, **11**, *115*.

Processes.

chanical properties of a welded joint, *J. Roy. Tech. College*, **4**, *304*.
nsile tests on welded joints, *Wärme*, **61**, *144* (Eng. Abs. **1**, Mech. *225*).
isceptibility of welded seams to the development of cracks, *Stahl und Eis.* **58**, *346*.
rinkage distortions and shrinkage stresses in welding, *Welding J.* (*New York*), **17**, *17*.
rman fatigue tests on welds. Experiments on the effects of shape of the ends of welded reinforcing-plates in tension members and of welded-flange stiffening-plates on girders, *Welding J.* (*New York*), **17**, *Welding Res. Supp.* **2**.

Lubrication.

e mechanism of wear in metals, *J. Roy. Tech. College*, **4**, *360*.
me factors that may determine the service life of tin-base bearing metals, *Tech. Pubs. of the International Tin Res. & Development Council Series A, No. 75.*

3. Shipbuilding and Marine Engineering.

rvice results with high-pressure boilers, *Trans. Inst. Marine Engrs.*, **50** (*3*), *1938*.
igh-temperature properties for some alloys of particular interest to the Navy, *J. Am. Soc. Naval Engrs.*, **50**, *107*.
eels and their utilization for high steam-pressures and temperatures (Paper read on the 12th April), *Institute of Marine Engrs.*, **50** (*4*).
mposium on propellers, *The Engineer*, **165**, *533*.
e qualities of a propeller alone and behind a ship (Paper read on the 31st March before the North-East Coast Inst. of Engrs. and Shipbuilders, Newcastle).

4. Mining Engineering.

) *Methods of Working.*

ressure effects on rock under stress from all sides, *Kohle und Erz.*, **35**, *26* (Eng. Abs. **1**, Min. *78*).
he design of chain coal-cutter picks, *Trans. Inst. Mining Engrs.*, **95**, *91*.

) *Explosives.*

etermination of the sensitivity to shock of explosives, *Zeit. ges. Schiess. und Spreng-stoff.*, **33**, *41* (Eng. Abs. **1**, Min. *83*).
he quenching effects of stone-dusts on coal-dust explosions, *Schlägel und Eisen*, **36**, *27* (Eng. Abs. **1**, Min. *97*).
nition of firedamp mixtures by explosives, *Ann. Mines*, **12**, *278* (Eng. Abs. **1**, Min. *84*).

) *Winding and Hauling Machinery.*

scillations in winding-ropes and their influence on mine stresses, *Bergbau*, **51**, *2* (Eng. Abs. **1**, Min. *88*).
Vear in pipe-lines conveying material for pneumatic stowage, *Glückauf*, **74**, *262* (Eng. Abs. **1**, Min. *104*).

) *Research.*

arbon-monoxide indicators, *Kohle und Erz*, **35**, *42* (Eng. Abs. **1**, Min. *85*).

5. Electrical Engineering.

(1) *Generation, Distribution, Machines.*

The resistance of nineteen metals to 30,000 kg/cm², *Proc. Am. Academy of Arts & Sciences*, **72**, *157*.
An extremely light high-potential battery of long life, *J. Franklin Inst.*, **225**, *401*.
A new high-tension voltmeter for relative and absolute measurements, *Archiv Ele*[k.], **32**, *44* (Eng. Abs. **1**, Mech. *284*).
Investigations on self-exciting asynchronous generators, *Archiv Elek.*, **32**, *1* (E[ng.] Abs. **1**, *256*).
A thyratron impulse generator, *J. Scientific Instruments*, **25**, *163*.
Voltage regulators, *The Engineer*, **165**, *526*.
Protection of electrical machinery against travelling-wave voltages, *Gen. Elec. R*[ev.], **41**, *101* (Eng. Abs. **1**, Mech. *264*).
Rural electrification, *J. Inst. Electrical Engrs.*, **82**, *333*; Line protection by Peter[sen] coils, with special reference to conditions prevailing in Great Britain, *J. Inst. El*[ec.] *Engrs.*, **82**, *387*.
The mechanism of the long spark, *J. Inst. Electrical Engineers*, **82**, *513*; A theory [of] fluctuation noise, *J. Inst. Elec. Engrs.*, **82**, *522*; The alternating-current resista[nce] of hollow, square conductors, *J. Inst. Elec. Engrs.*, **82**, *537*.
*Air-dielectric cables, *Elec. Rev.*, **122**, *641*.
Plastics and electrical insulation (Paper before Inst. E. E., 24th March).
Solution of electrical networks by successive approximations, *Univ. Illinois E*[ng.] *Expt. Stn., Bull. 299*.

(2) *Telegraphy, Telephony, Television.*

Polar molecules in the earth's electric field as absorbers of wireless waves, *J. Frank*[lin] *Inst.*, **225**, *309*.
Pre-striking currents in a thyratron, *Phil. Mag.*, **25**, *649*.
Direct determination of the electrical constants of soil at ultra-high radio-frequen[cies], *Phil. Mag.*, **25**, *793*.

(3) *Miscellaneous Applications.*

A magnetic comparator metal-thickness tester, *J. Scientific Instruments*, **25**, *156*.

6. Other Branches of Engineering.

(1) *Aeronautical.*

Gliding and soaring flight (Lecture at Royal Institution, 5th March), *Nature*, **1**[41], *712*.
Instability of monocoque structure in pure bending, *J. Roy. Aero. Soc.*, **42**, *291*.
The effect of wing loading on the design of modern aircraft, with particular regard [to] the take-off problem, *J. Roy. Aero. Soc.*, **42**, *369*.
High wing loading and some of its problems from the pilot's point of view, *J. R*[oy.] *Aero. Soc.*, **42**, *405*.
Aero Res. Cttee. Reports and Memoranda.
Visibility of light signals, with special reference to aviation lights, *No. 1793*.
Some aerodynamic characteristics of tapered wings fitted with flaps of various spa[ns], *No. 1796*.
Wind-tunnel tests on the effect of extreme slipstream on single and twin-engin[e] monoplanes with split or slotted flaps, *No. 1797*.
Nomenclature for stability coefficients, *No. 1801*.
Full-scale water resistance of the Singapore IIC in steady motion, *No. 1805*.

rther measurements of the full-scale water resistance of a IIIF seaplane in steady notion, No. *1806*.

rsional oscillation of a cantilever when the stiffness is of composite origin, *No. 1809*.

alysis of routine tests of monoplanes in the Royal Aircraft Establishment free-spinning tunnel, *No. 1810*.

tional Advisory Committee for Aeronautics, Reports. Comparative flight and full-scale wind-tunnel measurements of the maximum lift of an aeroplane, *No. 618*.

ag of cylinders of simple shapes, *No. 619*.

e variation with Reynolds number of pressure-distribution over an airfoil section, *No. 613*.

essure-distribution over an N.A.C.A. 23012 airfoil with an N.A.C.A. 23012 external-airfoil flap, *614*.

Automobile.

gine bearing temperatures, *The Engineer*, **165**, *505*.

enomena between road and tyre ; wear and safety, *Auto. Zeit.*, **41**, *52* (Eng. Abs. 1, Mech. *280*).

Illuminating, Heating, Ventilating and Acoustical.

eliostat illumination of buildings, *The Engineer*, **165**, *426*.

flexion factors of acoustical materials, *Trans. Illuminating Engineering Soc.*, **33**, *373*.

flectivity of corrugated surfaces, *Physica*, **4**, *1181*.

new method of gas-heating by radiant plates, *Rev. Universelle des Mines*, **80**, *179*.

he thermal conductivity of some specimens of pumice concrete, *N.Z. J. Sci. Tech.*, **19**, *585*.

ndensation within walls, *Heating, Piping*, **10**, *49*.

he prevention of the transmission of sound along water-pipes, *Proc. Physical Soc.*, **50**, *360* ; The transmission of sound in a building by indirect paths, *Proc. Phys. Soc.*, **50**, *368*.

he prevention of noise in buildings, *J. Roy. Inst. Brit. Arch.*, **45**, *117*.

Engineering Materials.

) *Timber.*

ontrol of carpenter ants in telephone-poles, *Connecticut Agric. Expt. Station, Bull.*, *403, 913*.

) *Stone, Bricks, Cement Products.*

rust-formation on building stones, *Korrosion und Metallschutz*, **13**, *409*.

trength, water-absorption, and resistance to freezing and thawing of sand-lime brick, *U.S. Bur. Stand. J. Research*, **20**, *67*.

elation between pore-size of bricks and their resistance to failure by freezing, *Am. Ceram. Soc. Bull.*, **17**, *92*.

orrelation of electrical and thermal properties of building-bricks, *J. Am. Ceram. Soc.*, **21**, *79*.

eats of hardening of Portland cements of different chemical composition, *Tsement*, **5**, *12*.

ome problems in the study of hydraulic cements, *J. Soc. Chem. Ind.*, **57**, *71*.

ontrol of cement quality, *Science et Ind.*, **21**, *2*.

oloured Portland cements, *Tsement*, **5**, *30*.

atex-cement compositions, *Bull. of the Rubber Growers' Assoc.*, **19**, *521*.

Testing of aggregates for durability in concrete, *International Assoc. for Tests Materials, London Congress, 1937, 348.*
Effect of type of test specimen and gradation of aggregate on compressive streng of concrete, *J. Am. Concr. Inst.*, **9** (*Proc.* **34**), *269.*
Determining concrete strength for control of concrete in structures, *J. Am. Con Inst.*, **9**, *285.*
Accelerated tests of strengths of cement products, *J. Roy. Tech. College*, **4**, *276.*
Plastic flow and volume changes of concrete, *Am. Soc. Test. Mat. Proc.*, **37**, *317.*
A simple test for water-permeability of concrete, *J. Am. Concr. Inst.*, **9** (*Proc.* 3 *65.*

(3) *Metals.*

Differential aeration as a factor in the localization of corrosion, *J. Soc. Chem. In* **57**, *98.*
The rate of corrosion of non-alloyed steel in air, *Stahl und Eis.*, **58**, *245.*
Corrosion by the impact of falling drops, *Engineering*, **145**, *521.*
Corrosion-resisting steels for chemical plant, *Chem. & Ind.*, **57**, *344.*
Influence of sunlight on the corrosion of iron, *J. of Applied Chemistry* (*U.S.S.* **10**, *1566.*
*The resistance of galvanizing to corrosion attack, *Stahl und Eis.*, **15**, *410.*
Research on thin layers of tin and other metals. IV. Further investigation on corrosi by oils, *Tech. Pubs. of the International Tin Res. & Development Council, Series No. 74.*
Light alloys and their use in engineering, *J. Junior Inst. of Engrs.*, **48**, *328.*
Alloys of the light metals, *J. Soc. Chem. Ind. Trans., 1938*, **57**, *69.*

(4) *Other Materials.*

Researches on rubber and rubber-like substances, *Chem. and Ind.*, **57**, *439.*
The influence of rubber upon some properties of bitumen, *De Ingenieur* (*Materi kennis*), **53**, *19.*
Weathering tests on filled coating asphalts, *U.S. Bur. Standards, J. Res.*, **20**, *159.*

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